JET PROPULSION PROGRESS

The Development of Aircraft Gas Turbines

The quality of the materials used in the manufacture of this book is governed by continued postwar shortages.

General "Hap" Arnold tells General Marshall and Admiral King of his conviction as to the revolutionary effect of jet propulsion for fighter aircraft. Bell test pilot Bob Stanley has just demonstrated the P-59A in a flight over Bolling Field, summer of 1944.

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The Development of Aircraft Gas Turbines

by

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JET PROPULSION PROGRESS

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Preface

IN THE MARCH of civilization, the form of transportation and communication that proves to be fastest, most comfortable, and cheapest always wins. As a means of propulsion on sea, on land, and in the air, the oar, sail, wheel, steam engine, steam turbine, and reciprocating engine have made mighty contributions and are still widely used.

During a few short years, a new prime mover has appeared on the scene; it has already forged to the front as the power plant of the world's fastest military aircraft—bombers as well as fighters—and it will find other highly important uses in the very near future. This is the gas turbine, which, as applied to aircraft, is being used in two principal forms: the jet-propulsion engine or turbojet; and the aircraft gas turbine with propeller drive or turboprop. The gas turbine also has immense possibilities for driving ocean-going vessels, helicopters, locomotives, or automobiles or even as an auxiliary power-plant system giving light, heat, and refrigeration in one reasonably compact unit.

The purpose of this book is to present simply and accurately the fundamentals of the gas turbine as applied to aircraft, with an outline of the development of such units in Germany, Great Britain, and the United States. Although a considerable amount of technical material has been included, elaborate calculations, engineering formulas, and highly technical discussions have been largely avoided.

Thus it is hoped that the volume may prove useful to students and to a rapidly increasing number of executives, businessmen, and professional men who are vitally interested in the problems of the air age that is now upon us. It is believed that members of the engineering fraternity will find the story of developments in the various countries (including a combined chronology of the principal events), a comprehensive bibliography, a glossary of technical terms, and other features to be of value as a source of reference.

Unlike radar, miracle maid of all work in World War II, jet propulsion was far from decisive in a military sense. A skeleton RAF fighter squadron, equipped with Meteor twin-jet fighters, shot down a few buzz bombs in the summer of 1944 and saw limited operational use on the Continent a few months later. In the fall and winter of 1944-1945, the Luftwaffe was

able to use the superior speed of the twin-jet Messerschmitt Me-262 Swallow to overtake and shoot down a few de Havilland Mosquito and Lockheed Lightning (F-5) reconnaissance planes, with their priceless cargoes of photographic material; to down several Allied fighters; and to break up, but not halt, a few heavy-bomber missions.

But, as many a cable from American air generals to AAF headquarters indicated, the threat of large numbers of successful German jet fighters in action by late summer 1945 was an ominous cloud on the horizon. This was confirmed by members of the Technical Industrial Intelligence Committee and other Allied experts, who have stated with much emphasis that, given another six months of jet propulsion development and underground dispersal of production facilities, the overwhelming air superiority enjoyed by the Allies after the spring of 1944 would have been seriously challenged and the war in Europe greatly prolonged or even ultimately lost. The section of this book dealing with German jet units which were in production, the Jumo-004 and the BMW-003, with their projected developments, and the Me-262, the only truly operational jet fighter in the war, should therefore be of great interest.

However, the main concern will probably center in the work of the British, which resulted from the flash of insight and the untiring toil of Frank Whittle (now Air Commodore, recipient of awards from the Royal Aeronautical Society and the Institution of Mechanical Engineers and now in charge of the government's entire gas-turbine developmental program); and developments in the United States, which stemmed from the Whittle design; also the work in this country stimulated by the National Advisory Committee for Aeronautics. In this section of the book (Chaps. Three to Six), the developments of the British, United States Army Air Forces, United States Navy, NACA, and American companies such as General Electric, Westinghouse, Allis-Chalmers, and Turbo Engineering Corporation are correlated.

In another chapter, the problems of heat-resistant alloys, special fuels for jet propulsion, maintenance of jet engines, and other special questions are briefly indicated. The future developments and possibilities of turbojets and propeller gas turbines for various types of aircraft, military and civil, including personal planes and helicopters, are surveyed in a final chapter. Notes on the secretly developed and highly promising "compound engine" are also included.

Acknowledgments are due to many who have directly or indirectly assisted in the preparation of this book. Foremost among these is John Foster, Jr., executive editor of *Aviation Week*, who collaborated with the authors in the chapter on jet propulsion developments of the United

States Navy. He augmented basic material prepared by a panel which collaborated during late summer 1945 on a projected joint release on jet propulsion under the auspices of the Office of Scientific Research and Development, similar to the releases on radar and on rockets. Mr. Foster rearranged for the book his articles on the Jumo-004, the Westinghouse 19B, and maintenance of gas-turbine jet engines and his notes on the Rolls-Royce Nene which were published in various issues of *Aviation*. He also provided valuable assistance in the mechanical arrangement of the book, bibliography, tables, etc.

The authors are indebted to Maj. Rudolph C. Schulte for his design analysis of the General Electric I-16 and the BMW-003, which originally appeared in *Aviation;* and for help in connection with the chapters on the United States Army Air Forces and German developments. Major Schulte was liaison officer at AAF headquarters on aircraft gas-turbine projects and also was a member of the American Technical Intelligence team appointed to secure complete information on the work of the Bavarian Motor Works, Germany, on aircraft gas turbines.

Much valuable material on German developments was obtained from an interrogation of the German engineer Helmut Schelp, by Lieut. S. T. Robinson, USNR (Naval Technical Mission to Europe), issued by the Combined Intelligence Objectives Subcommittee, SHAEF. Material on the development and tactical uses of the Me-262 was largely derived from intelligence sources of the British Air Ministry and the United States Army Air Forces.

Main sources of material on British developments were Air Commodore Frank Whittle's first James Clayton Lecture delivered before the IME, London, on The Early History of the Whittle Jet-propulsion Gas Turbine; Dr. H. Roxbee Cox's ninth Wright Brothers Lecture presented before the Institute of the Aeronautical Sciences in Washington on British Aircraft Gas Turbines; and a paper read by Group Capt. G. E. Watt at the engineering conference on aircraft gas turbines held under the auspices of the Army Air Forces and General Electric Company at Swampscott, Mass., and entitled Review of Aircraft Gas-turbine Development in the United Kingdom. This last paper was furnished through the courtesy of N. S. Muir, chief, engine development section, British Air Commission, Washington, who was also helpful in other ways. A member of his staff, Squadron Leader J. W. Adderly, was also helpful with the chapter on British developments and supplied some useful notes on the German developments.

Thanks are due Reginald G. Standerwick, E. S. Thompson, and others in the aircraft gas-turbine division of General Electric for checking the facts in connection with the development by their company of aircraft gas

turbines as recorded in the chapter on the Army Air Forces and for several technical and factual comments which were incorporated in the text. D. Roy Shoults of General Electric (now chief engineer of Martin), who was one of the key figures in the American development of the Whittle-designed jet engines, also aided in preparing the chapter on United States Army Air Force developments. In addition to making several useful technical comments, he supplied in the rather complicated narrative a number of links that greatly increased its value.

Col. Donald J. Keirn, project officer on jet propulsion at Wright Field and liaison between the AAF and the British, further enriched the chapter by performing a similar service. Some basic AAF material was derived from two articles in *Air Force* by Maj. Robert V. Guelich.

Special thanks are due R. P. Kroon and Charles D. Flagle of Westinghouse Electric Corp. in connection with the Navy chapter and design analysis of the 19B turbojet. Robert E. Littell, aeronautical engineer with the NACA, not only supplied most of the material comprising the chapter on NACA activities but was chairman of the panel that worked on the projected joint release on jet propulsion which was to cover the part played by NACA, Army, Navy, and industry in this field.

The authors are especially grateful to their good friend Dr. Jerome C. Hunsaker, chairman of NACA, for contributing a foreword.

No attempt has been made in this volume to provide a complete history of aircraft gas turbines or to mention the many designs, patents, and experimental projects in various countries or to deal with the detailed engineering principles involved. This has been ably done by G. Geoffrey Smith, MBE, to whom great credit should be given for his pioneering writings (in the magazine *Flight* and elsewhere) on this subject, in the midst of wartime restrictions, which resulted in his book "Gas Turbines and Jet Propulsion for Aircraft," now in its fifth edition. The objective has been instead to provide an outline, with a reasonable amount of illustrative detail, of the fruitful developments in this new field which began in the mid-thirties.

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Foreword

WITHIN THE lifetime of many of us, the speed of human flight has been advanced from the first tentative attempt at gliding at some 10 mph to more than 10 mpm. Progress in man's conquest of the air cannot, however, be represented by a continuous rising curve but rather by an irregular series of upward steps, each step marking the successful application of an important advance in some aspect of aeronautical science. Some steps were greater than others, and we are likely to call these improvements revolutionary. But we have witnessed only the typical pattern of an advancing technology applied to the Wright brothers' basic concept of an airplane: a heavier than air vehicle supported and controlled by aerodynamic forces as it is driven forward by virtue of the power of a gasoline engine turning a propeller.

The airframe and its power plant until now have remained the same in principle. The wings have been refined in form, and the propeller and engine have grown in output from the 40 hp of the Wright brothers to more than 3,000 hp. Further improvement in the engine appears to be increasingly difficult to secure, but higher speeds require very much more power from a much lighter power plant.

The war-developed gas turbine meets these requirements for both power and weight and today offers to the airplane designer a power plant of the turbojet type able to drive an airplane at radically higher speeds. In fact, the art of airplane design is not yet able to deal with such speeds crossing the transonic barrier and entering the supersonic region.

We have a true revolution in aeronautics caused by jet propulsion. We make a sharp break away from the Wright brothers' concept of an airplane when we replace the engine and propeller by the new jet-propulsion unit. This break with tradition forces the designer to seek new aerodynamic forms and new means of control to cope with higher speeds. He is in the paradoxical position of having more power than he dare use.

We are at the threshold of human flight through the 750-mph speed of sound. Beyond this so-called "transonic barrier," where our aerodynamic laws change radically in their nature, lies the promise of flight at supersonic speeds. For this, new aerodynamic knowledge is needed. It is being acquired by research at great cost and by experience at great risk. Never-

theless, the pioneers of the laboratory and of flight are meeting the challenge to complete the conquest of the air.

Besides the present revolution in the art caused by the turbojet power plant, we must anticipate for supersonic speeds the possibilities of the ramjet—a power plant without moving parts. Such a "flying stovepipe," of 20-in. diameter and weighing but 400 lb, is estimated from laboratory tests at the NACA to give a thrust equivalent to some 20,000 hp at 1,500 mph. Some time will pass before an airplane can be built to fly at 1,500 mph, and perhaps we shall not recognize such a supersonic vehicle as an airplane. It might first be a missile guided by robot mechanisms.

In the supersonic regime, the propeller cannot function. At extreme altitudes, where there is little or no air, neither the propeller nor any form of engine can operate. Here we must depend on the rocket for propulsion. The rocket carries its own oxygen for combustion and gives a thrust that is virtually independent of speed or altitude.

Man is now learning to live in a world shrunk by air-transportation speeds in the 200- to 300-mph range. In this relatively low speed range the gas turbine and propeller have attractive applications for commercial aircraft of the immediate future. The gas turbine also has a promising area of usefulness in surface transportation by ship and by locomotive.

We consequently find ourselves in a revolutionary phase of transportation made possible by a new and more effective power unit. To appraise its future, we need only look upon the vast complex of new industries that were born of the reciprocating gasoline engine.

The present volume fills a need for a book covering international developments in the aircraft gas turbine from an American point of view. The authors have been in a position to follow these developments closely, and they have presented them objectively, clearly, and accurately. For general information and as a handy reference volume for schools, colleges, and industry, it should fulfill a useful purpose.

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JET PROPULSION PROGRESS

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CHAPTER ONE

The Weapon behind the Revolution

An aeronautical revolution is today sweeping the skies clean of established concepts of speed and altitude, bringing new horizons of military and commercial activities that will be second in importance only to the atomic bomb in making or breaking civilization.

It is a revolution springing from a new form of power—jet propulsion. Yet, though jet propulsion burst upon the world during World War II as a new secret weapon, its principle has been known and understood for more than 2,000 years. Philosophers and scientists have been working for over 20 centuries to give it practical military or peacetime application.

That jet propulsion is truly a revolutionary development is shown by the swift advances since the first successful jet-propelled flight was made less than eight years ago. Already it has revised all military fighter-plane design considerations and tactics; already it is being felt in bomber designs and strategy; soon it will be felt in air-transport operations.

And with these changes come new words to the language: *turbojet*, a gas turbine plus jet; *turboprop*, a gas turbine plus propeller; *motorjet*, a conventional reciprocating engine plus ducted fan; *turbofan*, a gas turbine plus ducted fan; *ramjet*, a continuous jet with compression by aerodynamic ram; and *pulsejet*, an intermittent-firing jet engine such as that first employed in the Nazi V-1 buzz bomb.

As Gen. H. H. Arnold, former Chief of the Army Air Forces, declared in his final report to the Secretary of War, "These new and strange-sounding words will be familiar ones in our speech in the near future, and right now they carry more meaning for Americans than any other six words I know of."

But whatever the name or form of application, every jet engine operates on one principle—Newton's third law of motion, which states that for every action there is an equal and opposite reaction.

As it applies to aircraft jet propulsion, this axiom can be most simply explained by an easily understood example. When a toy balloon is blown up and the tube held closed, the compressed air inside presses with equal force in every direction against the sides, and the balloon will lie motionless. But, release the tube, and the balloon will whisk away in the direc-

tion opposite the tube. The motion is imparted by the reaction of the still compressed air pushing against the side away from the tube.

Though the principle was not given "legal" status until Newton put it in the form of a "law," it was understood at least 2,000 years ago by Hero, an Alexandrian mathematician. In attempts to utilize the power that could be so developed, he drew up plans for a sphere that had two short nozzles bent out from opposite sides. This sphere was then to be suspended on two sealed tubes which extended down to the top of a steam boiler. When the water was heated, the expanding steam would force its way up through the tubes into the sphere and escape through the nozzles, with the resulting reaction turning the sphere.

Newton himself drew up plans—undoubtedly unsuccessful—to put his law of reaction to practical work on what might have been the first horseless carriage. His plans called for mounting, on a coach frame, a large spherical boiler with a jet nozzle coming out the top and pointing aft. The idea was then to get up steam in the boiler and let the jet shooting out through the nozzle drive the whole affair.

Though the reaction principle was the basis for these and a great many other experiments, it should be noted that all were concerned with the steam turbine, a prime mover that has been of immeasurable importance in large stationary power plants and in ocean-vessel propulsion. And, just recently, it has invaded the American railroad field with experimental models undergoing service tests.

It was not till 1791 that John Barber, an Englishman, went into the field of gas turbines. As G. Geoffrey Smith writes:

> . . . the sketch which accompanied it [the patent] was, perhaps naturally, very rudimentary and certainly it provided no clue to the technical possibilities of the design. The proposed plant comprised a gas producer, gas receiver, gas and air compressors, a combustion chamber, a turbine wheel and speed-reducing gear. . . . Relative efficiency would not arise at that early period, and it can only be assumed that it was desired to produce a prime mover less complicated than the boiler, engine, and condensing equipment of the steam plant and to obtain rotary motion without the need for the crank and connecting rod mechanism.

It took man nearly 150 years to achieve that desire, and it would probably have taken much longer if the major nations had not been plunging toward the most destructive war in history, as will be shown in later chapters detailing developments in Germany, Great Britain, and the United States.

But in the 8 years since the Nazis made the first jet-propelled flight, advances in the art have been almost breath-taking; developments of basic

designs have been as swift and far-reaching as any other in the aircraft industry, which, perhaps more than any other, is known for evolutionary strides.

As the art stands today, there are two basic types of gas turbine: the centrifugal and the axial flow. Variations of each have already been developed, and the two types have been combined.

In both cases, however, the principle of operation is the same. Air—with its combustible oxygen—is taken into the unit by the impeller or compressor, and its pressure raised from three to five times. This air is then forced into the combustion chamber (or a ring of chambers) where it is allowed to expand a little. At the same time, fuel, such as kerosene or gasoline, is sprayed in by high-pressure pump and ignited.

This combustion greatly expands the air, which means that it has to have more room; and out toward the exhaust is the only way it can go. But, as it rushes toward the exhaust jet, it has to pass through the turbine wheel, which is fixed to the same shaft as the compressor. Thus, the air pushing out turns the turbine, which in turn runs the compressor and pulls in more air. Not all the power in the air is required to run the turbine, though, and it is the excess energy which forms the jet the reaction to which pushes the whole plane forward.

Centrifugal turbojets thus far have two main subtypes: reverse flow, like the early Whittle British and General Electric American engines; and the through-flow. In the former type, air is taken in through an impeller and whirled out—centrifugally, as in a cream separator laid on its side—to be compressed, then turned 90 deg and headed aft. Then, to save length and the complications of added weight of shafting and bearings, the air is turned 180 deg and into the combustion chamber where the fuel is added and burned. But, to get the thrust in the right direction, the air must again be turned nearly 180 deg to go through the turbine and out the exhaust jet.

In the through-flow type, the air goes through the same type of impeller and is turned aft and slightly inward to go directly through the turbine and out the exhaust. This arrangement provides a much more efficient and powerful operation and, with modern design, an engine not greatly longer than the reverse flow.

In the axial-flow type, air is taken in through a multistage compressor like a series of fans or propellers and is compressed as it flows straight back toward the combustion chamber for addition of fuel and ignition and then right on out through the turbine and exhaust. This type naturally is somewhat longer than either of the centrifugal types but can be

made with a much smaller frontal area, a factor of great importance to the aeronautical engineer who wants the least possible resistance (drag).

Both centrifugal and axial-flow types have already been combined with conventional propellers as one means of overcoming one of the jet engine's inherent weaknesses: the fact that at low altitudes and slow speeds, it cannot compete in efficiency with the conventional reciprocating engines

After an airplane leaves the ground, it can fly with a substantial overload. This JATO unit is a booster for take-off with overload. Developed as a military accessory, it is now commercially available. Four of these units on a Douglas DC-4 increase its allowable take-off weight by 7,000 lb, which can be added directly to pay load.

and propellers which have heretofore powered aircraft. This application, and other technical details of the various types, will be discussed at greater length in those sections of the book devoted to the engines themselves.

Often badly confused with the turbojet engine is the rocket, possibly because it operates on the same basic principle of reaction. But that is about the end of the similarity. The main difference is that the rocket carries all its own fuel, either solid or liquid, together with the necessary oxygen, or oxygenizing agent, to burn the fuel; whereas the turbojet takes the necessary oxygen out of the air through which it passes.

Although rockets have long been of military importance—and may well be of infinitely greater importance in the future—their peacetime application seems much more limited than gas-turbine jet propulsion.

Like the turbojet, the rocket burst upon us as a "secret weapon" during World War II, when the Nazis started their fortunately belated V-2 campaign against England. But as long ago as A.D. 1232, Genghis Khan's son Ogdai employed rockets as a secret weapon against Kaifeng, the Tatar city.

Probably the most important peacetime rocket use, at least until interplanetary flight becomes possible, will be in the war-born JATO (jet-assisted take-off), powerful rocket units serving as auxiliary power plants to help heavily laden planes get into flight within the confines of airports or harbors with greatly increased pay loads. Thus, the rocket may well play an important part in future aeronautical developments, but it is a separate study in itself which can be touched upon only incidentally here.

Though the amazingly swift advances in turbojet development are an enduring tribute to the comparatively small group of men who made them possible, there are still many problems to be overcome. Problems of fuel economy, of combustion, of metallurgy, of lubrication, of dozens of other factors have made the turbojet's development a constant story of men accomplishing the impossible. What those problems were, how they were met, what problems still remain, how they are being met, and what can be expected from the future are disclosed in the following chapters that give the story of the men and the machines that they created.

CHAPTER TWO

How the Nazis Beat Us to It

Although it was not known until after the war, the Germans were the first to fly a jet-propelled airplane, for they made the world's first such flight on Aug. 27, 1939—four days before the Wehrmacht invaded Poland.

This flight, made by a Heinkel 178 used as a flying test bed and powered by an HeS-3 turbojet, was not the result of an overnight miracle. It was, rather, the first fruits of a long-range, carefully planned program designed to keep the Nazis' air supremacy as one means of subjugating the entire world.

How closely they came to success is known but not yet generally appreciated, and the part played by the aircraft gas-turbine program is discussed in some detail here as one means of clearly showing the importance of continued research and development.

To evaluate properly Germany's contribution to the development of the aircraft gas turbine, it is essential to view it in connection with her entire research program, for only now is it possible to get a clear picture of German accomplishments up to the end of World War II, together with the long-range scientific programs that were projected as far ahead as 1950 and beyond.

Close study of the accomplishments and plans reveals that the Germans were not scientific supermen. They did not produce any miracles. But they did show what can be done by applied engineering effort in developing weapons of war. They did demonstrate that engineers, plus funds, plus time, can accomplish almost any desired result. It is only fortunate for us in the United States that we had the time to mobilize our top engineers and the funds to achieve the results that they did. This is true not only in turbojet work but in other fields, such as applications of microwave radar by British physicists and engineers at the Telecommunications Research Establishment and our own National Defense Research Council's Radiation Laboratory at Massachusetts Institute of Technology.

Serious German research on military aeronautics began in 1934 after the rise of Hitler to power, but its roots go back at least five years earlier. From the first, there was great emphasis on experiments leading toward

the ultimate development of rocket-powered aircraft and guided missiles, an example of the absolute necessity to cut clear of mere orthodox thinking and strike out with daring and highly imaginative conceptions. By 1932, the experiments had shifted from crude and uncontrolled rocket projectiles to the more or less automatically controlled rocket plane.

In 1934, rocket studies and aeronautical research generally were given a tremendous shot in the arm by the establishment of the Deutschen Versuchsanstalt für Luftfahrt (DVL) at Adlershof, near Berlin. This establishment was given funds tenfold greater than those granted to America's NACA. This was not all, for but within a couple of years two similar research and development centers were begun. In addition to this, huge sums were granted to German industrial firms for specialized research and development work in purely military aeronautical projects.

The year 1936 saw the establishment of a great rocket and turbine program at Peenemunde on the Baltic Sea. It was divided into two separate departments: One was operated by Ordnance for the development and testing of rocket projectiles and wingless missiles; the other, by the Reichsluftfahrtministerium (RLM) for the development of winged missiles and rocket-propelled aircraft. This latter section also included a flight-test base for testing jet aircraft and winged missiles.

The dividing line between the two divisions at Peenemunde was whether the particular gadget had wings (RLM) or not (Ordnance). This point of view has emerged in discussions in the United States, but our Air Forces have established the additional consideration that they have a strong interest in both classes of development, especially in genuine long-range rockets, because of the distinctive character of another possible war as an air war. Thus, 1934 saw the beginning of the accelerated program in German rockets and military aeronautics, but it was not until 5 years had elapsed that the Nazi leaders were ready to plunge the country into war. Not until the High Command believed the nation had scientifically outstripped its marked enemies did they take the fateful step. It was anticipated that a decision would be forced long before her enemies could be prepared.

Jet developments were started very early in the German program, for as far back as 1930 Professor Prandtl of Junkers Flugzeug und Motoren Werke at Dessau began basic research on gas turbines. And Ernst Heinkel, one of the most versatile of the German aeronautical designers, kept his firm interested in the subject, beginning that same year. Heinkel became particularly interested in gas turbines about 1935 through young Dr. von Chain, who took out several gas-turbine patents about this time. His

basic patent is well known, but it was filed under the name of Max Hahn for camouflage reasons.

In the mid-1930's engineers of the Bayerische Motoren Werke (BMW) at Munich began preliminary research in jet propulsion, and some beginning calculations on gas turbines began to take shape at the Junkers' Dessau plant.

All these projects, however, were independent and uncoordinated ventures, and it was not until near the end of 1938 that RLM began seriously to take over.

RLM's interest might well be said to have started here in America, however, when a young man named Helmut Schelp was busy getting a master's degree at Stevens Institute in Hoboken, N. J. Schelp returned to Germany in 1936 and soon afterward went to work for RLM. The following year he began work on gas turbines and, in 1938, was made head of the department responsible for their development. He then made a tour of all reciprocating-engine manufacturers to persuade them to push turbojet developments. Whether or not Schelp was at fault, the idea was not very well received; but by the end of 1938, he had BMW and Junkers working on what later became the BMW-003 and the Jumo-004 (both of which are analyzed in detail at the end of this chapter). He was not successful with Heinkel, for, as an Allied intelligence report has it, "Schelp had heard reports that Heinkel was building a turbojet engine but was unsuccessful in getting him under his wing or getting him to discuss it with him."

Schelp's having "heard reports that Heinkel was building a turbojet" turns out to be one of those minor military masterpieces of understatement, as the Heinkel turbojet was already on the test stand and, as noted, a few months later made the world's first flight. The engine was not a great success, however, for the airplane was quite slow, and the life of the engine very short. Only a few flights were made before Heinkel went to work to develop the HeS-8 unit designed to power the He-280, a twin-jet fighter. This craft flew in 1941; but development was dropped, as the green light had been given the more promising Messerschmitt Me-262.

In the autumn of 1939, Heinkel took over controlling interest in the Hirth engine firm and moved all gas-turbine work from Rostock to the Hirth plant at Stuttgart. Development proceeded very slowly, though, and in 1941 Heinkel approached RLM for support. (His HeS-8 was tried in an Me-262 in 1941, but the units were not powerful enough to get the craft off the ground.) Up to this time, Heinkel had insisted on working independently, but he now asked RLM for a design that he could develop. As a result, he was given the HeS-11, first known in this country as the

"Heinkel-Hirth 011" but later given the German designation "109-011 A-O."

Progress was still very slow, however, and not one of the units had flown under its own power at the end of the war. Bench tests developing of 2,860 lb static thrust [1] at 10,200 rpm were reported, but only one or two flight tests were made, with the unit being installed under the belly of a Ju-88.

The compressor of the Heinkel-Hirth 011 consists of an axial-flow mixer fan followed by a diagonal, or mixed-flow, stage plus three axial-flow stages. Other features include an annular combustion chamber, a two-stage turbine, and an adjustable tail cone. Weight was 2,085 lb; diameter, 34.4 in.; and length, 138.1 in. (Engineering notes will be found on page 51.)

It was not until 1941 that Schelp succeeded in persuading Daimler Benz at Stuttgart to enter the gas-turbine field. Their first design, the DB-007 by Professor Leist, proved extremely complicated, and it was abandoned after a short time when the company was switched to development of a propeller version of the Heinkel-Hirth 011. On the other hand, from 1939 on, both BMW and Junkers were directed to a considerable extent by the RLM and worked in close collaboration with each other. By the end of that year, in fact, design work on the Jumo-004 was under way. The first design was a small-scale version of that unit, built for test work only. It was unsuccessful because of combustion difficulties and was abandoned when work on the full-scale engine was started.

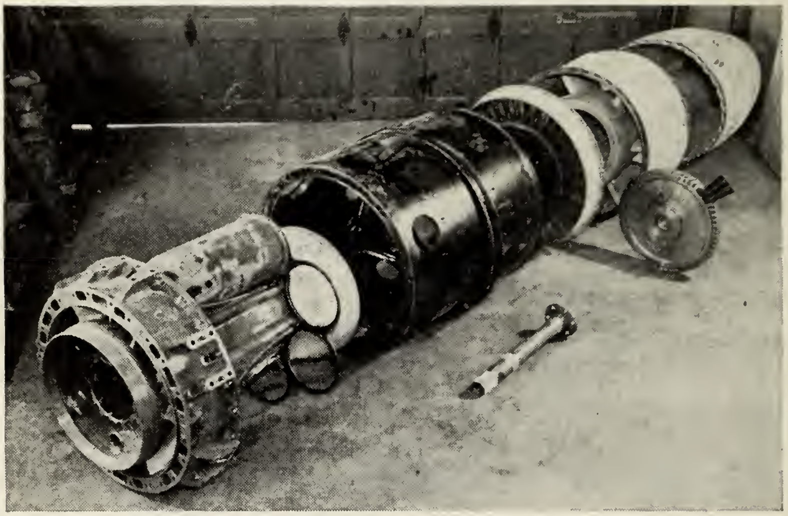
This unit was test-run in December, 1940, and flight-tested in a modified Me-110 about a year later. In July of 1942, a prototype of the Me-262 was test-flown, powered by two Jumo-004B's. The first production models of this plane, called the Swallow, flew in the spring of 1943. Static sea-level thrust was 1,975 lb at the relatively low figure of 8,700 rpm, its maximum, due to the lack of high-quality heat-resistant lightweight alloys. For this same reason, actual service life span averaged only about 10 hr.

The Jumo-004 was the first operational German gas turbine for jet propulsion and went into large-scale production at Dessau in the spring

[1] Because the power output of a reaction engine varies widely with the speed of the vehicle in which it is installed, jet engines are rated in static thrust at sea level instead of horsepower. At 375 mph, 1 lb of thrust equals 1 hp. At higher speeds of the vehicle, greater horsepower is developed for the same thrust. At lower speeds, the horsepower is proportionally lower. This is the reason why pure jet engines had to await the development of faster planes in order to be effective power plants. For a formula for converting thrust into horsepower, see Glossary, p. 215. This explains why pure jets, without propellers, would be hopelessly inefficient for slow-moving vehicles like automobiles and boats.

of 1944, with some 6,000 units being produced before the German collapse. Most of them went into Me-262's, some in Arado Ar-234's, and a few in experimental models of the big four-jet Junkers Ju-287 bomber.

A noticeable lag in gas-turbine development came in 1940, when the German High Command shifted emphasis from research to production. In the winter of 1943-1944, however, when American heavy bombers



Exploded view of the aft portion of the Junkers Jumo-004. *Left to right:* main casting, with one combustion chamber in place; combustion chamber case; turbine shaft (beside case); turbine nozzle; turbine (in line with shaft) with three blades in place; and exhaust system broken into two major components. (*Courtesy of Aviation.*)

with long-range fighter escort began to dominate the daylight skies over Germany, development was hastily resumed. Within a year, designs were completed and construction of prototype units begun on the improved Jumo-004D and H versions, with 11-stage axial-flow compressor (instead of 8-stage) and 2-stage turbine (instead of single-stage). Design thrust was more than double that of the production Jumo-004B, or 3,960 lb.

The BMW-003 project was begun in 1939 with a design thrust of 1,300 lb. Construction was completed in the late spring of 1940, and the first unit test-run in August, 1940. This was a smaller, more compact engine than the Jumo-004, with a seven-stage axial compressor and single-stage turbine. First results were disappointing, and the engine was redesigned in 1942 as the BMW-003A. Static sea-level thrust eventually attained by this improved version was 1,760 lb at 9,500 rpm. The unit was so prom-

ising that when the first flight of the Me-262 powered by two Jumo-004B turbojets took place in the summer of 1942, Junkers were ordered to produce the Jumo-004 as it stood and reduce all development and modification work to a minimum. At the same time, BMW were told to develop the BM-003 to such a level that it would become a good replacement for the BM-004 at a later date, when Junkers was to be given an opportunity to resume development work.

The BMW-003A was flight-tested in the fall of 1943 in a Ju-88, and it went into production early in 1944. During the next 15 months, some 750 units were produced at Spandau, near Berlin.

The C version of the BMW-003 had a compressor of Brown-Boveri design, with other minor improvements to increase performance. (This was a German Brown-Boveri Company, associated with the great Swiss company during peacetime.) Static sea-level thrust was 1,880 lb at 9,500 rpm. A BMW-003D was designed in 1944, with eight-stage axial compressor and two-stage turbine, having design thrust of 2,420 lb at 10,000 rpm, according to findings of an American Technical Intelligence team which discovered the first unit under construction at the BMW factory at Spandau.

During the summer of 1945, it was learned by the American Technical group led by Dr. Theodor von Kármán, special adviser to General Arnold, that the Germans had an ambitious 12-year program for development of gas turbines, rockets, and guided missiles.

Under this program, power-range requirements for aircraft to be powered with turbojets were set up by RLM as shown in the following table:

Table I

Class	*Thrust, pounds*	*Pressure ratio*	*Turbine stages*
I	Up to 2,200	3.5:1	1
II	2,860-3,740	5.0:1	2
III	5,550-6,600	6.0:1	2
IV	7,700-8,800	7.0:1	3

The class designations applied to both turbojet and turboprop units, with a program designed to develop turboprops from the basic turbojet engines from Classes II, III, and IV. One additional turbine stage was to be added to Class III, and two on the Class IV engines in the propeller-turbine work.

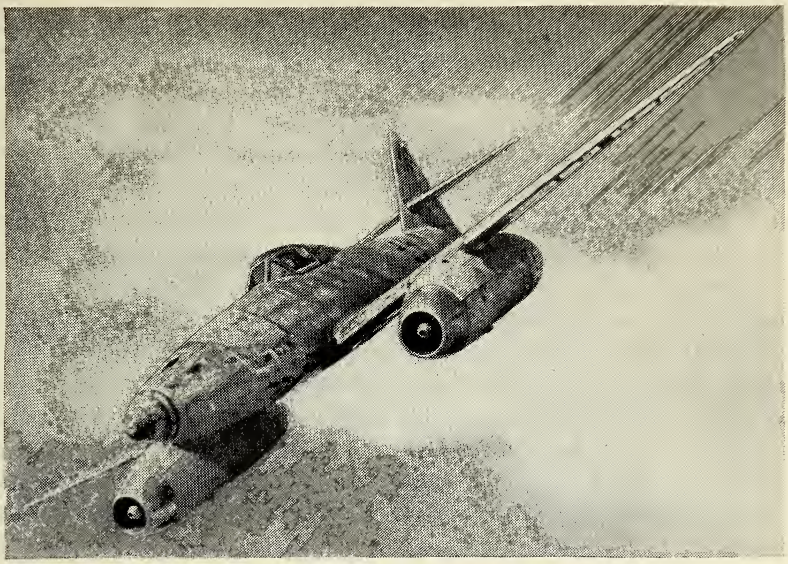
The first 4-year stage of the 12-year program began in 1939 and was to have been completed by the end of 1942 with large-scale production of the Jumo-004 and BMW-003, with the Heinkel-Hirth 011 coming in about halfway through this preliminary period. The program lagged by at least 2 years, but as a result of a highly concentrated effort the Allies were beaten to the punch in at least one respect.

During the autumn and winter of 1944-1945, a substantial number of Me-262's and a few Arado-234's were put into operational use, an achievement in which the Germans took considerable pride. A number of urgent messages from Gen. Carl Spaatz, chief of the United States Strategic Air Forces, to Army Air Force headquarters indicated the concern of the operational leaders in the theater regarding this potential threat to Allied air superiority. In early autumn of 1944, the speedy Me-262's, then not too numerous, were for the most part ignoring our adequately escorted heavy bomber formations and concentrating on the priceless strategic air reconnaissance of American F-5's (photographic Lockheed Lightnings) and British Mosquitoes. For some time, the jet planes were shooting down so many that our photo-reconnaissance planes had to have fighter escort. A stopgap was urgently called for until the Allies could get an honest 500-mph fighter into the European skies.

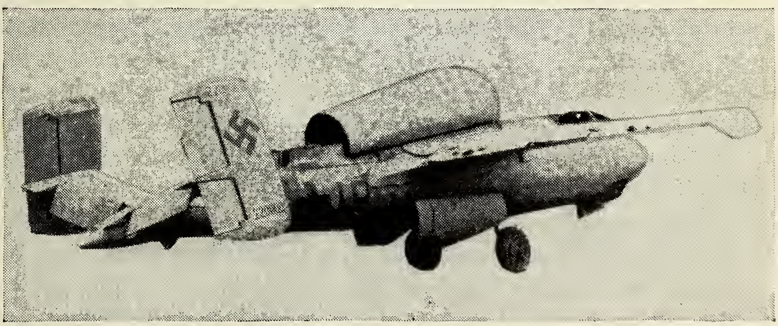
The conventionally powered fighter planes then available were not that fast; and the Lockheed P-80 Shooting Star, although fast enough, had only recently been test-flown. Production was not under way; and the jet-fighter training program, using Bell P-59A Airacomets, was just gaining momentum. The British Gloster Meteor had been in the hands of an RAF fighter squadron in small numbers since May and was soon after engaged in defense against the V-1 buzz bombs.

An "off-the-cuff" answer to Spaatz's urgent call was the hybrid Republic P-47M Thunderbolt—the then current P-47D-30 fuselage with the new C version of the Pratt & Whitney R-2800 Double Wasp, scheduled to go into the 1945 P-47N long-range Thunderbolt. The M was really fast, with a top speed of better than 475 mph—a good 50 miles faster than the standard escorting Thunderbolts—and gave our forces a very valuable element of tactical surprise when it went into action.

A typical combat report indicates what our then available fighters were up against. An Me-262 engaged three North American P-51 Mustangs in a 20-min fight at low altitude over a German airfield—and escaped undamaged. The encounter began when the AAF planes, escorting a photo-reconnaissance Mosquito in February, 1945, sighted a jet-propelled aircraft over Leipheim airdrome at an altitude of 700 ft. When the P-51's had closed to 500 yd, the pilot of the Me-262 made a turn to the right.



The Messerschmitt Me-262 was the first jet-propelled fighter to go into combat and was the only one to see extended service. Powered by two Junkers Jumo-004 turbojets, it had a high speed of over 600 mph. (*Courtesy of Aviation.*)



The Heinkel He-162 was one of Germany's many radical designs with which the Nazis attempted to recapture command of the skies. A combination wood and metal craft, it was powered by a BMW-003 turbojet mounted in the duct atop the fuselage. (*Courtesy of Aviation.*)

The P-51's attempted to turn inside but lost sight of the Me-262 when drawing proper lead. After several turns, the Me-262 straightened out and streaked away, the P-51's following. The Me-262 made a 180-deg turn and led the Mustangs back across the airfield through a barrage of flak. This procedure was repeated *nine times.*

The Me-262 flew at altitudes ranging between 500 and 3,000 ft. According to the AAF pilots, the P-51's turned in a tighter circle, but the Me-262 traveled so rapidly in a larger circle that their shots fell well behind. All turns were made in almost a vertical bank, which caused the bullet paths to be obscured by the plane's nose. Maximum speed obtained by the Mustangs during the combat was 390 mph. The Me-262 was estimated to have been 100 mph faster—enough to make all the difference in the world.

However, under other conditions, both Me-262's and the Me-163 rocket interceptors were shot down or damaged by the best Allied fighters, including American Mustangs and Thunderbolts and British Spitfires and Tempests to a total of several dozen. Early combat intelligence reports of the Me-262 in action noted its high speed and rapid climb but relatively poor maneuverability. Two such reports covering the first week of November, 1944, were typical.

A flight of Eighth Air Force P-51's escorting bombers south of Bremen on November 6 spotted two Me-262's at about 6,000 ft proceeding along the bomber track. The jet fighters gained on the four pursuing Mustangs while in level flight; but when they turned to the left, a P-51 closed in and started firing. One Me-262 reversed direction, pulling over in front of another P-51, which promptly shot it down. These tactics were effective because the P-51's bracketed the Me-262 so that it was unable to speed away to its base. During an encounter on November 1, in the Enschede-Lingen area, an Me-262 turned into a P-47 which turned with the jet-propelled aircraft and got on its tail, shooting out the right jet of the Me-262. The German fighter went into a flat spin, and the pilot bailed out.

One early criticism of the German jet fighters was the extremely long take-off and landing run. This was true of the Me-262, both as fighter and bomber, and especially true of the Ar-234, encountered in small numbers from about November, 1944. To overcome the long take-off run, rocket-assisted take-off was employed.

In an interview with high-ranking officers of the Air Prisoners of War Interrogation Detachment in Europe, Reichsmarshal Hermann Göring threw some interesting light on the employment of the Me-262. Asked the reason for the delay in using it as a fighter, Göring stated somewhat excitedly that when the first Me-262 left the assembly line in March, 1944.

he had presented it to Hitler as the fighter that would sweep Allied air-power from the skies. But Hitler insisted that it be converted into a "blitz bomber." He ordered that the armament—four 30-mm cannon—be removed, that one 500-kg (1,100-lb) or two 250-kg (550-lb) bombs be carried instead, and that extra fuel be carried in the front to restore the balance and increase the range.

Top leaders of the German Fighter Command tried to buck Hitler on the issue, and finally Göring was compelled to dismiss the ringleader, Lieutenant General Galland, German ace and chief of the Fighter Command, who had been the first Luftwaffe pilot to fly the Me-262 (in May, 1943) and was very enthusiastic about it.

Because of all these arguments, the Me-262 was, fortunately for the Allies but greatly to Göring's regret, kept from its most effective use for several months. Hitler finally did make one concession. American fighter intrusions over German territory were becoming so troublesome that, as Göring put it, "Mustangs were practically doing training flights over Bavaria." In order to stop "this nonsense," Hitler permitted the recall of Galland, who was given a small fighter unit of 16 Me-262's for which he picked the most experienced pilots he could find.

Finally, toward the end of 1944, Hitler gave permission to use the Me-262 as a fighter on a larger scale. But it was then much too late. He was finally convinced of its high effectiveness as a fighter when, in January, 1945, ten of the type attacked a long string of heavy bombers and shot down ten.

The German plan finally called for an Me-262 fighter belt running from Holland through Belgium to northern France, where the jet aircraft would engage the Allied bombers' fighter escort, forcing them to jettison their auxiliary tanks and return home, leaving the bombers unprotected. The bombers were then to be attacked over Germany by conventional fighters armed with 30-mm cannon and airborne rockets. Luckily, because of the rapid advance of the Allies through Belgium and France, the plan was never put into full operation.

Göring also reported that development of the best tactics for jet aircraft was still in the experimental stage and depended on the number of Me-262's available for an attack. Up to the end of the war in Europe, no more than 40 Me-262's were employed on any one mission.

From another source, a report has been obtained of the Me-262 as a night fighter, in which it was largely thrown against RAF Lancaster bombers. In this capacity, it carried the usual armament in front plus radar intercept equipment. It also had two upward-firing heavy machine guns installed in the fuselage. The first attack was level from behind;

and if this were unsuccessful, the Me-262 flew under the bomber, blazing away with the upward-firing guns. Excellent results, some of them confirmed in Allied reports, were claimed by the Me-262 night-fighter pilots.

A few notes on the Me-262 as a bomber will serve to complete this brief outline of the only jet-propelled aircraft on either side that can truly be said to have reached operational status. The information is derived from interrogation of an Me-262 pilot who had been in the program from the start and was familiar with its role as bomber, day interceptor, and night fighter, and who was captured during the final days of the struggle in Germany.

Apparently, the deepest penetration of behind Allied lines by Me-262's with bombs was 160 mi, flying at an altitude of 13,000 ft, with four planes abreast. Speed to the target was 420 mph! Each plane carried two 500-kg bombs under the nose, which was double the load originally ordered by Hitler. Prior to February, 1945, the Führer, in order to prevent the airplane from falling into Allied hands, forbade any Me-262 bomber to fly under 13,000 ft. Pilots complained of the effect of this order on bombing accuracy, and it was changed to allow them to go down to any altitude that they considered safe.

If Allied fighters were encountered on the way to the target, the usual evasive action was to "turn on the heat" and climb away. Antiaircraft fire was evaded by increasing speed and weaving from side to side. The maximum diving angle was 35 deg, pilots diving from 13,000 to 3,200 ft or so, taking care to prevent the air-speed indicator from going over 570 mph. Me-262 pilots used the old Revi bomb sight, which was supposed to be accurate to within 125 ft. Following release of bombs, the Me-262's streaked home at 450 to 475 mph at between 3,500- and 4,000-ft altitude.

Altogether, some 1,400 of the Me-262's in various series were produced. Allied Technical Intelligence has estimated that more than half were lost through engine failure, through inexperienced piloting, or by being shot down by Allied fighters and/or antiaircraft artillery. Thus, it seems clear that Germany, desperate to avoid defeat, rushed her jet aircraft into the air without sufficient type tests. The Luftwaffe took delivery of engines that the British and American air forces would have found completely unacceptable. Their short running lives and lack of reliability were a serious embarrassment in service. A comparison of the contemporary Rolls-Royce Welland and Derwent I and the General Electric Type I-40 with the Jumo-004 and BMW-003 demonstrates that on the basis of thrust-weight ratio, specific fuel consumption, and endurance in service the German engines were outclassed.

However, it is important to remember that all this was only the first phase of the German gas-turbine program. Those in the best position to know are emphatic in their testimony that, given another year—possibly only six or eight months—the picture in the air over Germany would have been vastly different.

For example, early in February, 1945, Maj. Gen. Fred Anderson, operational deputy to General Spaatz, told General Eisenhower at his headquarters in Paris (SHAEF, Main) that if the ground forces didn't take Germany by June, the Germans' rate of production of jet and rocket planes would make it impossible for the great armadas of 1,000 heavy bombers with 800 escorts to continue to bomb Germany by day without losses that might make the bombings militarily unprofitable. Fortunately, Field Marshal Montgomery's and General Bradley's armies took care of this situation within the following 90 days.

Given another short lease of life, though, it is believed that many of the bugs would have been eliminated from the production of Jumo-004B, including the use of a recently developed heat-resistant alloy that would have increased its life span as well as its thrust. The BMW-003 would have been in full production, and possibly the very promising Heinkel-Hirth 011 would have been available for some of the new crop of fast jet fighters. These included the He-162 Volksjaeger, or "People's Fighter," a small, lightweight interceptor which, according to Göring, was a result of the most intensive collaboration of all the important experts in the field of jet designing, including top men with Heinkel and Messerschmitt. The plane was designed and built in 74 days, the first one being delivered in December, 1944, but crashing 2 days after. The second model, embodying certain improvements, attained a speed of 520 mph. An original production schedule called for an initial output of 500 per month, gradually increasing to 1,000 a month, in underground factories. This ambitious program was prevented largely by the hopelessly chaotic state of German communications by the end of 1944 and by the German policy of subcontracting the manufacture of component parts of the aircraft. These two factors prevented the manufacture of anything but a small number of the He-162's. At first, the power plant was the BMW-003, to be replaced by Heinkel-Hirth 011 if and when this unit became operational.

In April, 1945, a brief report was received of the newly operational He-162, including photographs and details of a P-51 combat encounter, taking place at an altitude of between 500 and 1,000 ft. The He-162 was said to be quite maneuverable, being able to turn, climb, and run very much the same as the P-51, and was faster on the straightaway. Although endurance was only 20 min, a force of several hundred He-162's to sup-

plement a flock of Me-262's could have posed a genuine threat to Allied air superiority by late summer, 1945, if the war had continued. This threat would have been not only against our heavy bomber formations; but, with increased range, the fast, heavily armed 262's could have played havoc with the closely packed airfields of both AAF and RAF bomber commands.

Interrogation of Schelp revealed that he considered the Heinkel-Hirth 011 the Germans' most promising long-range project, a view that was shared by members of the Messerschmitt organization. Next he rated the BMW-003, and after that the Jumo-004, although he did not blame the Junkers people entirely, since they had been forced to concentrate on production until the BMW-003 could be developed as a replacement for the Jumo-004.

Schelp also revealed that the Germans, just before their collapse, were starting development of water injection, with which they expected to get thrust increases of as much as 80 per cent for short periods of time. This was to be accomplished by one or all of three principle methods: (1) by injecting water into the eye of the blower, increasing mass flow; (2) by injecting it into the combustion chamber, increasing energy level; and (3) by injecting it into the turbine blades, increasing the cycle temperature.

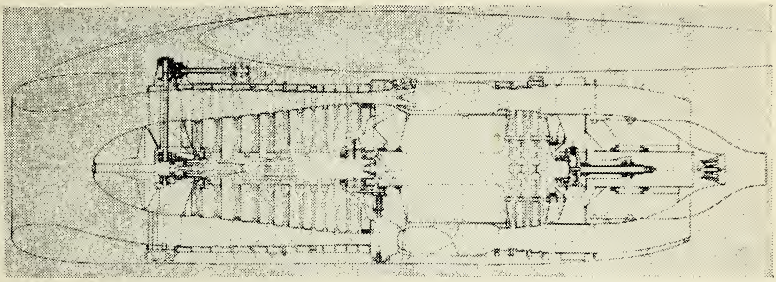
The second method, according to Hirth calculations, would yield a 38.5 per cent increase with only a modest addition of water. BMW experiments on the same method showed actual increases ranging up to 25 per cent, using twice as much water as fuel. Combustion-chamber injection was abandoned, however, because of adverse effects on compressor efficiency; and injections aft of the combustion chamber gave no thrust increase.

Afterburning experiments were also tried by BMW, but they were not so successful as Junkers—who got 11 per cent increases on the Jumo-004—owing to the shorter tail pipe on the BMW-003. BMW did not push the afterburning experiments, since they considered their BMW-003R (a BMW-003A with rocket attachment) to be a more satisfactory answer.

The second phase of the long-term jet program, stated to run from 1942 to 1945 (but at least two years behind schedule), was the development of more powerful versions of the BMW-003, Jumo-004, and Heinkel-Hirth 011 to be used in new, faster fighters such as the EF-128 and Focke-Wulf 183, on which wind-tunnel tests had been completed by the spring of 1945.

In addition, new and much larger units in the 6,000- to 8,000-lb thrust class, designated "Jumo-012" and "BMW-018," were scheduled for de-

velopment. Work on these began in 1944, but in neither case was a complete unit built by May, 1945. The Junkers Jumo-012 was to have an 11-stage axial-flow compressor, two-stage turbine, eight individual chambers, and adjustable tail cone. Design weight was 3,520 lb; diameter, 43 in.; length, 194 in.; with static sea-level thrust, 6,100 lb. The BMW-018 was larger and heavier though actually a bit shorter; weight, 5,060 lb; diameter, 49.3 in.; length, 165 in. Design thrust was 7,500 lb at 6,000 rpm. The 12-stage axial-flow compressor was found completed at Spandau, with the rest of the engine under construction, including 3-stage turbine,



Cross section of the 109-018 12-stage compressor, which BMW had managed to build before the Germans' defeat. Designed to operate at altitudes up to 50,000 ft, the unit was designed to have a static sea-level thrust of 7,500 lb at 6,000 rpm. (*Courtesy of Aviation.*)

annular combustion chamber, adjustable tail cone, compression chamber 7 atm. These powerful turbojets were to be used to establish a fast, hard-hitting bomber force composed of the Ar-234C, the Ju-287, the He-343 (since abandoned), and others, all with four jet units. Pending completion of the big gas turbines, both the Ar-234C and the Ju-287 were fitted with BMW-003 units and test-flown, the only jet-propelled heavy bombers to have taken to the air before the end of the war. They were faster than then operational Allied fighters.

Still another part of Phase 2 were modifications of the Heinkel-Hirth 011, the Jumo-012, and the BMW-018 from gas turbines for jet propulsion to propeller drive. These carried the designations "021," "022," and "028," respectively, but none had gotten beyond the design stage by war's end.

The final 4-year period 1946-1950 was planned for the third phase of the program. This was to have been characterized by the development of huge aircraft of the flying-wing type powered by the units referred to above; development of supersonic aircraft with ramjets; accurately controlled long-range guided missiles hardly to be classified as aircraft at

all; and other weapons to stagger the imagination. Basic research for all this and more was very largely completed by the summer of 1945, when Allied forces overran the whole of Germany.

Thus, it is evident that it was not entirely an idle boast back in 1940 when the Nazis proclaimed that their military aircraft program was well in hand for 6 or even 8 years ahead. They had the necessary imagination, the men, the money, and the research facilities in staggering proportions —and it is far from pleasant to contemplate how near they came to realizing their objectives.

Detailed investigation and interrogation by Allied Technical Intelligence teams lead to the conclusion that one of the greatest omissions in the German development of aircraft gas turbines was a strong and energetic centralized research organization for this particular purpose. Certainly the equipment that they had at their disposal at the various plants was so extensive that they seemed to gloat over it for its own sake, and some of the brains in research establishments were as good as any in Great Britain or the United States. There seemed literally to be no lack of funds. However, to a considerable extent, their research organizations worked in a vacuum, and poor liaison between the research workers and the production firms undoubtedly robbed the German engine industry of many fruitful developments. As will be shown in the next chapter, this valuable function was provided in Great Britain by the Gas Turbine Collaboration Committee set up by the Ministry of Aircraft Production, and to some extent in the United States by a Committee on Gas Turbines and Jet Reaction Engines organized by NACA.

In addition to the Germans' lack of effective liaison between research organizations and industry, an additional weakness was brought to light. With typical Teutonic thoroughness, a large amount of precalculation on designs was made by RLM, and the direction of the entire program by the Ministry was firm and rigid, resulting in a somewhat stereotyped approach to design problems which is shown by the general similarity of all German turbojet units, with the exception of the He-011. This is in strict contrast to the almost entirely competitive system adopted in the United States and with the loose system in England of combining collaborating private enterprise with government direction, both of which allowed much freer reign to the individual designers.

Nevertheless, as in Gilbert and Sullivan's "Patience":

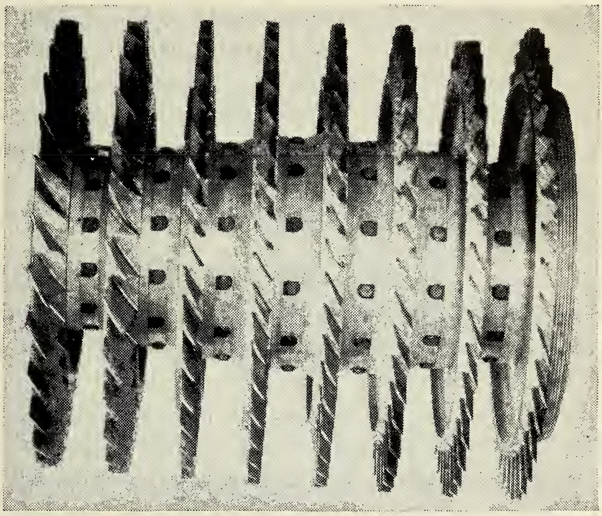
"No doubt! Yet, spite of all your pains,
The interesting fact remains—"

the Germans *did* get their jets in the air well ahead of the Allies, and the

threat *was* formidable enough to give our high command and air leaders plenty of sleepless nights.

THE JUNKERS JUMO-004 TURBOJET [2]

As is the case with the air frame of the Me-262, the Junkers Jumo-004 axial-flow gas-turbine jet-power plant is a compromise between design desire and available materials and production facilities.



Jumo-004 eight-stage axial-flow compressor, showing how each compressor section is bolted together on shoulders of individual disks. (*Courtesy of Aviation.*)

Outstanding evidence of compromises resulting from lack of materials is the fact that more than 7 per cent of the air taken in is bled off for cooling purposes. Despite this, however, most engines were found to have a service life of about only 10 hr, against a "design life" of 25 to 35 hr. Additional compromises are evident in the design, which shows that the production engineer—undoubtedly hampered by lack of both plant facilities and adequate skilled labor—has been as important a factor in its construction as was the designer.

But the Germans had made real progress in overcoming material difficulties, for just after they capitulated it was discovered that development of a new alloy of excellent heat-resistant qualities had made it possible

[2] Based on a design analysis of the Messerschmitt Me-262, by John Foster, Jr., which appeared in *Aviation*, Vol. 44, No. 11, November, 1945.

to get up to 150 hr service in actual flight tests and up to 500 hr on the test stand.

A large unit, the Jumo-004 is 152 in. long from the intake to the tip of the exhaust and 30 in. in diameter at the skin around the six combustion chambers, with maximum diameter of the cowling reaching 34 in.

The circular nose cowling is double skinned, the two surfaces being welded together near the leading edge and held in position by riveted channel-shaped brackets. Diameter at the intake end is 20 in., the outer skin increasing to 31½ in., the inner to 21½. Inside the cowling is an annular gasoline tank which is divided into two sections, the upper being of ¾-gal capacity, feeding fuel to the starting engine; the lower, of 3¾-gal capacity, feeding starting fuel to the combustion chambers.

The nose cowling attaches by eight screws in captured nuts to the annular-shaped combination oil tank and cooler. Having 3-gal capacity, this tank has a baffle close to the inner surface, so that as warm oil is fed in from the top it is cooled as it flows around to the bottom of the annulus and the tank proper.

The oil tank, in turn, is attached by 23 bolts on a flange to the aluminum-alloy intake casting. This unit comprises the outer ring, with flanges on both front and rear faces; four hollow, streamlined spokes; and the inner ring.

Moving back to the front of the unit, though, we find inside the nose cowling a fairing that looks just like a propeller spinner, increasing in size to 12 in. at the intake casting, leaving approximately 220-sq in. intake area. This spinner houses the starting engine, a two-cylinder, two-cycle, horizontally opposed gasoline engine that develops 10 hp at 6,000 rpm. The starting engine has its own electric starting motor; and, for emergency, extending out to the front of the spinner is a cable starter similar to those found on outboard boat engines. The engine is 12½ in. long, 10 in. wide, and 8¼ in. high and weighs 36 lb.

The starter engine is bolted to six studs in the bevel-gear casting, which contains gears to drive the accessories. Each of these gears is carried by ball-and-roller bearings, with the drive shafts fitting into internally splined stub shafts on the bevels. There are two drive shafts extending through two of the hollow fairings of the intake casting, one going up to the accessory case, which is mounted atop the intake casting; the other, extending down to the main oil pumps, which are set inside the lower part of the intake casting.

The bevel-gear casting, also of aluminum alloy, is bolted to 12 studs set in a flange in the front face of the intake casting.

The rear side of the intake casting's inner ring is cup-shaped, housing the front compressor bearing. This unit is comprised of three thrust races —each with 15 bearings—mounted in steel liners set in a light hemispheric-shaped housing, which is kept in contact with the female portion of the intake housing by the pressure of 10 springs held in place by a plate bolting to the intake casting. The outer bearing races are mounted in separate sleeves that fit on the compressor shaft.

Not only does this design allow for preloading the bearings during assembly to ensure even distribution of thrust, but also the bearing assembly can be left intact during disassembly simply by withdrawing the compressor shaft from the inner sleeve.

Next in the fore-to-aft sequence is the aluminum-alloy stator casting, which is built in top and bottom halves held together longitudinally by eleven ⅜-in. bolts through flanges on each side, with attachment to the intake casting by twenty-four ⅜-in. bolts through a heavy flange. Running the entire length of the bottom half of the casting are three 0.7-in.-diameter passages, one serving as part of the oil line leading to the rear compressor and turbine bearings, one connecting oil sumps (which are located in both intake and main castings), and one serving as part of the oil return line from a scavenge pump set in the rear turbine-bearing housing.

Just aft of the fourth compression stage in both halves of the stator casting is a slot, inside which is a ring with a wedge-shaped leading edge pointing upstream and set to leave a 0.08-in. opening to bleed off air for part of the cooling system (which will be discussed later in a separate section).

Like the stator casting, the stator rings, which consist of inner and outer shroud rings and stator blades, are built as subassemblies, then bolted in place and locked by small tabs.

Considerable variation, both in materials used and in methods of construction, was found in this section. In early production units, for example, the inlet guide vanes and first two rows of stator blades were of stamped aluminum with airfoil profiles; and in assembly, ends of the blades had been pushed through slots in the shroud rings and brazed in place. In other early engines, the third stator row varied both in material and in method of attachment. In some cases, it would be of aluminum but without airfoil; in others, it would be of steel with the ends turned to form flanges that were spot-welded to the shroud rings. The remainder were stamped sheet steel, zinc coated.

One late-production engine examined showed a combination of all the variations, with inlet guide vanes and first two rows of stator blades of stamped aluminum, and the rest steel, indicating that the Germans may

have been swinging over from aluminum to steel exclusively. Apparently, all the steel blades had been enameled, but this protective coating on the last row, where temperatures reached approximately 380°C, appeared to have been burned off.

Methods of attaching blades to shroud rings also varied. On the inlet guide vanes and first two rows, the ends of the blades had been pushed through slots in the shroud rings and brazed in place; the third, sixth, and seventh rows had a weld all around the blade end; the fourth-, fifth-, and eighth-row blade ends had been formed into split clips which were spot-welded to the shroud rings.

The outer shroud rings are channel-shaped, with an angle bracket riveted to each end, this bracket in turn being bolted to a stud set in the casing just inside the mating flange. Inner shroud rings are flanged along the leading edge, with the exception of the seventh row, which is channel-shaped.

Except for the inlet guide vanes and the last row of stator blades, which act as straighteners, stator blades are arranged as impulse blading—they are set at nearly zero stagger and simply serve as guides to direct the air flow into the rotor blades.

The compressor rotor is made up of eight aluminum disks held together by 12 bolts each through shoulders approximately at mid-diameter, with the entire unit being pulled together by a 38.75-in.-long, 0.705-in.-diameter tie rod which has been estimated to have a stress of some 40,000 psi, with a force to pull the assembly together figured at about 16,000 psi.

Diameters of the disks increase from the low- to high-pressure ends as follows: Stage 1, 13.86 in.; Stage 2, 14.68 in.; Stage 3, 15.61 in.; Stage 4, 16.44 in.; Stage 5, 17.18 in.; Stage 6, 17.85 in.; Stage 7, 18.24 in.; and Stage 8, 18.34 in.

To carry the compressor bearings, there is attached to each end disk a steel shaft with an integral disk carrying a round-faced washer. This shaft goes through the disk and is tightened by a nut so that the face of the washer (rounded to facilitate alignment) bears against the disk face. The flange on the rear shaft has six slots around its outer edge, into which fit projections on the rear disk. Thus, torque is transmitted from the turbine to the rear compressor disk, and from there on to the other disks by the bolts previously noted as fastening the disks together, the torque being transmitted to the compressor unit around the faces, rather than through a central shaft.

Compressor rotor blades, of which there are 27 in the first two stages, 38 in the rest, are all stamped aluminum with machined roots fitting into pyramid-shaped slots in the rotor disk. Through the aft face of each blade

root, directly under the blade trailing edge, is a small screw set longitudinally and extending into the disk.

Tip stagger of the blades is about the same through the first six stages of compression but increases in the last two. Chord of the blades decreases through the eight stages as follows: 1.95, 1.94, 1.34, 1.33, 1.30, 1.30, 1.24, and 1.21 in.

Blade profiles in the first two stages are very similar (possibly even designed to the same section), but the third stage has a thicker section. Stages 4, 5, and 6 have thinner sections (here, too, possibly the same), with about the same chord as Stage 3, whereas the last two stages, though set at greater pitch and having slightly narrower chord, have generally similar chamber and profiles.

Clearances between the rotor blades and the stator casting are 0.103 in. over the first three stages and 0.04 over the remaining five. Axial clearances between rotor disks and inner stator shroud rings range from 0.1 to 0.15 in., and axial clearances at the roots between rotor and stator blades are 0.5 and 0.6 in.

Backbone of the Jumo-004 is a complex aluminum casting which, in addition to providing the three engine attaching points, supports the compressor casting—through 25 bolts—the entire combustion-chamber assembly; the turbine nozzle; the aft compressor bearing; the two turbine bearings; and, through the combustion chamber casing, the entire exhaust system. Moreover, in the base of each of the six ribs supporting the combustion chambers, there are cored passages, five of which carry cooling air, one carrying lubricating oil. And while the air-passage area remains constant between the compressor and combustion chambers, the main casting changes the shape from annular to circular at the entrance to the chambers.

In the front of the casting, at the tip of the last stator row, is an $18\frac{3}{8}$-in.-diameter ring with a serrated inner surface fitting closely to serrations on the aft face of the last compressor disk. Air bleeding through the serrations is carried aft through cored holes in the casting to cool the front face of the turbine disk and, on hollow-bladed turbines, to cool the blades themselves.

Just outside and in back of this ring are the fairings that divide the air and direct it into the individual combustion chambers. These fairings, in turn, are surrounded by a 28-in. o.d. ring with 25 boltholes for attaching the compressor casing. Besides the boltholes, there are 18 openings, 6 of which carry the air bled off from the compressor on aft for exhaust-system cooling; and 12 smaller ones, which take cooling air around the combustion chambers.

Around the outside of this ring, extending back to a heavy flange to which the combustion-chamber casing bolts, are 12 raised longitudinal ridges arranged in pairs. These have machined faces having four boltholes and two aligning pins serving as the forward-engine pickup points. With six such pickup points, the engine was designed for a wide variety of mountings. In the case of the Me-262, plates with collared nuts were fastened to the two on either side of the topmost unit.

Over-all length of the main casting is $37\frac{1}{4}$ in., with the previously mentioned ribs tapering down from the aft face of the ring structure to the central longitudinal member, which has an $8\frac{3}{4}$-in. diameter at the aft end.

The aft compressor bearing, having 16 rollers, is set in the front of the main casting inside the serrated ring, the housing being attached to the casting by 14 bolts.

The turbine thrust bearing is set inside the main casting, with the center line of the balls $24\frac{3}{8}$ in. back of the front edge of the serrated ring; and the main turbine roller bearing is bolted into the rear end.

Each of the six combustion chambers is built up of three major components having a combined weight of 19 lb. First, there is a mild-steel outer casing, of $5\frac{3}{4}$-in. diameter at the entering end, flaring out to $8\frac{5}{8}$ in. and having a length of $20\frac{5}{8}$ in. The front end has a collar with a rubber sealing ring which is pushed up against the aft face of the main casting to take care of air leakage and to compensate for the difference in casting and combustion-chamber expansion.

Fitting inside the front end of this casing is the flame tube, which has two main components—the entry section and the stub-pipe assembly. The forepart of the entry section flares out somewhat as does the outer casing and at the front end has a six-blade swirler. This unit is made of 22-gauge mild steel with a black-enamel coating. The stub-pipe assembly is made up of 10 flame chutes welded to a ring (which is welded by brackets to the rear end of the flame tube) and to a 4-in. dished baffle plate at the rear. To help direct air into the chutes, $\frac{1}{2}$-in. circular baffle plates are riveted to the forward ring. Material of this unit is mild steel with an aluminized finish.

Third major component of the combustion chamber is an 11-in.-long, 20-gauge aluminized-steel liner having a corrugated outer skin that permits cooling air to flow inside the outer casing. This liner fits into the aft end of the casing. The aft ends of the combustion chambers are bolted around flanges to a ring of six rings that fits over the rear end of the main casting.

Ignition interconnectors between chambers are of but $^{15}\!/_{32}$-in. diameter, and starting plugs are provided in three of the six chambers. These elements, as are the fuel plugs, are enclosed in streamlined fairings.

Surrounding the combustion chambers is a 16-gauge, mild-steel, double-skinned casing having flanges welded at both ends—that at the front end attaching by studs to the main casting; that at the rear, attaching to the turbine inlet-duct outer flange, the nozzle-ring assembly flange, and the exhaust-casing flange. Besides the boltholes in the front flange, there are 24 of similar size—12 leading to six ducts of 22-gauge steel which carry the air bled from the fourth compressor stage through the combustion-chamber casing; and 12 directing air around the combustion chambers. These ducts also help stiffen the skin, as it takes the weight of the entire exhaust system.

Six large handholes are cut in the casing just behind the flange. These give access for making minor adjustments to burners and the three ignition plugs.

A little more than halfway aft around the combustion-chamber casing is a heavy collar comprised of two channel-shaped members; and inside the casing at this ring are six tie rods, connecting it to the main casting. Any one of these six units can serve as the aft-engine pickup point; in the case of the Me-262 it is the top one.

Ducting from the combustion chambers to the turbine nozzle changes the air passage from the six circles to annular shape. Attached to the combustion chambers by bolts, this 19-gauge, aluminized, mild-steel unit is made in two parts, the rear of which is welded to a heavy flange. Studded to this flange from the inner shroud ring of the turbine-nozzle assembly are two mild-steel diaphragm plates. These, in turn, are studded to the rear end of the main casting and so support the inlet ducting and turbine-nozzle ring. On the rear of the outer turbine-inlet ducting, a light flange mates with a flange on the rear of the combustion-chamber casing. Thus, the turbine-inlet ducting, to which the combustion chambers are attached, is supported partly by the main casting, partly by the diaphragms, and partly by the skin.

Maintenance crews really take a beating as the result of the final design, for it is a major operation to get at the combustion chambers. First, the variable-area nozzle-operating shaft must be removed so that the complete exhaust-system assembly can be taken off. Then, unless special equipment is available, the engine must be placed upright on the turbine disk, and burner pipes and ignition leads disconnected from the combustion chambers. Then the compressor casing-main casting joint can be broken, and the whole front end of the engine lifted off. Next, the

rear compressor bearing assembly, torque tube, and locking ring can be removed, and the main casting assembly removed—when the nut on the front end of the turbine shaft is unscrewed. The rear diaphragm plates can then be removed, and the turbine-inlet ducting and combustion-chamber assembly lifted off. Then the front diaphragm plate is removed, and the turbine-inlet ducting, with the combustion-chamber assembly, lifted out of the casing. At this point, as one sweating engineer who did the job declared, "Now, Bub, y'can take out the individual combustion chambers."

An unusual feature of the Jumo-004's design is the use of hollow turbine-nozzle blades through which cooling air is fed from the compressor via the main casting and supporting diaphragm plates. The two-part outer nozzle-shroud ring is made of mild steel, and both parts are welded to a ring that is joggled and flanged to mate with flanges through 36 bolts on the inlet ducting and the aft flange of the combustion-chamber casing. In addition to the boltholes, the flange has 36 sets of three holes for cooling-air passage.

The 35 nozzles are made of austenitic sheet steel, 0.045 in. thick, bent to shape around a $\frac{1}{16}$-in. radius to form the leading edge. Between the sheets at the trailing edge are spot-welded four wedge-shaped spacers, 1 in. long and tapering from $\frac{1}{8}$ to 0.020 in., leaving a 0.020-in. gap down the trailing edge through which the cooling air escapes.

In assembly, the blade tips are closed and pushed through slots welded to the outer shroud ring, and the roots are pushed through slots in the inner shroud ring and spot-welded in place on the inner surface of the ring.

To this ring, in turn, is welded a heavy, mild-steel flange and second flanged ring, the two flanges picking up with the diaphragm plates that support the assembly from the rear of the main casting.

Two types of 61-blade turbine are used. Originally, both blades and disks were solid; later, hollow blades and lighter disks were introduced at a saving of approximately 40 lb.

The solid disks were of hardened chrome steel, taking stresses of about 15 tons at maximum rpm. Cooling is effected by spilling air bled back through the main casting against the disk face, then up over the blade roots and out between the blades.

The $12\frac{1}{4}$-oz solid blades are forged from an austenitic steel containing 30 per cent nickel, 14 per cent chrome, 1.75 per cent titanium, and 0.12 per cent carbon, corresponding closely to "Tinidur," a Krupp alloy known before the war, and are attached by three machined lugs drilled to take two 11-mm rivets each. Maximum centrifugal blade stresses have

been estimated at 18,000 psi, and gas bending stresses at 2,000 to 4,000 psi. Study of the solid blades indicates that the roots did not get much above 450°C, because of the cooling air flow up from the disk; but near the center, it appears that the temperatures got up to about 750°C. This applies to service models, not those previously mentioned as having given the longer flight and test-stand life.

Disks for hollow-blade turbines are of lighter material than the solid types and have attached, across the front face, a thin sheet flared out near the center. This picks up the cooling air and, via ridges on the disk, whirls it out toward the blade roots, where it goes through two small holes drilled in the disk rim up through the blade and out the tip.

Made of the same material as the solid blades, the hollow type are formed by deep drawing a disk through a total of 15 operations. In assembling the turbine, the blade roots are fitted over grooved stubs on the disk rim. Two small holes on each side take locating pins to hold the blades in place during assembly, but they take no stresses.

With a silver-base flux in the grooves, the entire unit is put in an oven at 600 to 800°C, warmed for 20 min, then heated to about 1050°C in 40 min, then cooled in still air at room temperature before hardening in a gas or air oven.

Later production units have two rivets in the blade trailing edges near the tips, a modification made necessary by cracking caused by vibration.

The turbine is attached by six studs to a short shaft carried on two bearings housed in the main casting. The front bearing is a single-race ball thrust; the rear, a single-race roller type; and both are cooled by oil only. Connection of the turbine and compressor is via a heavy, internally splined coupling.

The exhaust cone is made up of aluminized mild steel and consists of two major components—outer and inner fairings. The outer fairing is double skinned, with cooling air bled from the compressor flowing between the skins to within 15¾ in. of the exit, where the inner skin ends. Outside the other skin from there to the end is another skin, flared at the leading edge to scoop in cooling air. It is attached by spot-welded corrugations.

Attached to the outer fairing by six faired struts is the inner fairing, tapering from 19½ in. at the turbine end to 9¾. This unit houses a rack gear—driven by a shaft entering through one of the struts—which moves a "bullet" extending from its aft end. Actuating this bullet over its maximum travel of approximately 7⅜ in. varies the exit area between 20 and 25 per cent. It is set in retracted position for starting to give greater area and help prevent overheating, then moved aft to decrease

the area and give greater velocity for take-off and flying. The movement is accomplished by a gear-type servo motor set near the accessory housing and connected by a long torque tube to gears set on the exhaust housing over one of the struts leading into the previously mentioned rack gear.

Originally, the unit was supposed to operate automatically over small ranges at extremely high speeds and altitudes to give maximum efficiency; but on some engines examined, the necessary lines had been blanked off. The two-position operation is obtained through a mechanical linkage with the throttle, so that the bullet moves aft at between 7,000 and 7,500 rpm.

Since the necessary cooling system played a very important part in both the design and the construction of the Jumo-004, it is felt best to note it briefly as a separate part of the study. It consists of three major stages, as follows:

1. Air bled off after the fourth compression stage
2. Air taken off just after the last compression stage
3. Air bled off between the compressor and combustion chambers

In Stage 1, the air is picked up by the ring after the fourth compressor row and is directed into six cored passages in the stator casting; then at the combustion-chamber casing it is divided so that some of it goes through six ducts in the combustion-chamber casing skin and some goes inside the casing and around the chambers themselves. That which goes into the ducts continues aft and, through small holes in the flanges, between the double skin of the exhaust-cone outer fairing. Most of the air goes straight on aft to the end of the inner skin, but some is taken through the six struts connecting the inner fairing into that unit to cool the rack gear and bullet.

In Stage 2, the air goes through the serrations between the compressor and the main casting into two of the six cored passages in the casting back to the turbine. Here, on the original engines, it was spilled against the face of the turbine disk and moved out to escape between the turbine blades, however; the air is ducted across the space between the two diaphragm plates supporting the turbine nozzles, then inside the sheet attached to the turbine disk, where it is picked up by ridges and forced up through the turbine-blade roots out through the blade tips.

Stage 3 cooling air, bled off between the compressor and combustion chambers, is ducted through three passages in the main casting to the space between the turbine-nozzle-supporting diaphragms, then up through

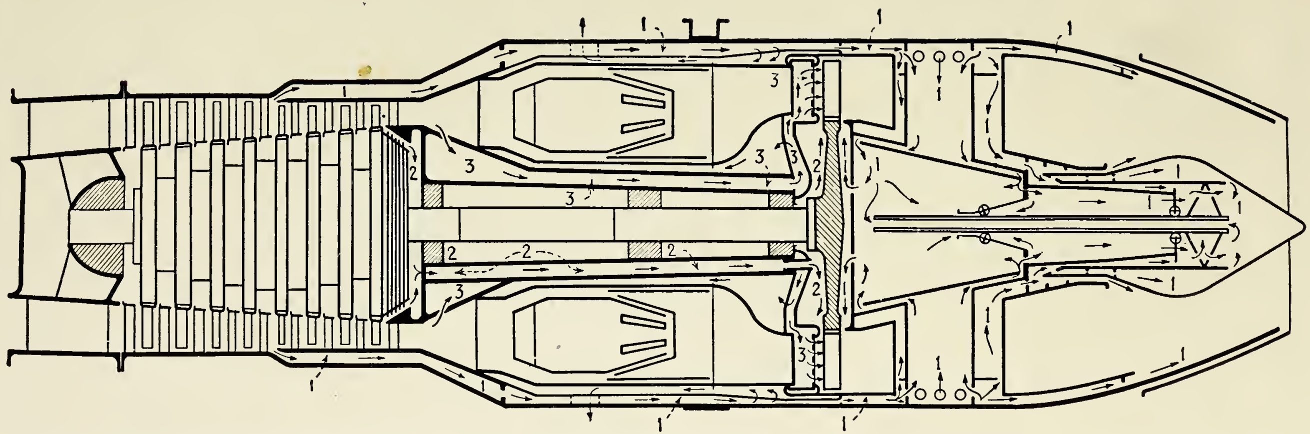


Diagram of the Jumo-004 cooling system, in which approximately 7 per cent of total air intake is bled off. Stage 1: cooling air, bled off just aft of fourth compression stage, cools exhaust system. Stage 2: air, bled through serrated rings on last compressor disk, passes through main casting to cool turbine disk. Some Jumo-004's had hollow turbine blades; this air was also directed through them. Stage 3: air, bled off between compressor and combustion chambers, is directed through main casting to cool turbine nozzles. (*Courtesy of Aviation.*)

the turbine-nozzle vanes and into the slip stream through the trailing edges of the vanes.

It is estimated that Stages 1 and 3 take approximately 3 per cent each of the total air movement and that Stage 2 probably takes at least half as much; thus, better than 7 per cent of the available flow is taken off because of a lack of higher heat-resistant alloys. Additional performance penalties are evident in the fact that ducting is necessary, complicating both the weight and production pictures.

Air is not the only cooling medium, for the lubricating system, too, is employed. In this system, two gear pumps circulate lubricating oil to the front compressor-bearing assembly, the accessory-drive bevel gears, and the accessory gears. Another supplies oil to lubricate and cool the rear compressor and both turbine bearings, the latter two being sprayed and splashed, respectively.

The two main pumps, mounted beneath the engine and driven from the bevel gears through a nose-casting strut, deliver 190 gph each. The two-part scavenge unit is built into the turbine-bearing housing and is driven by a gear cut into the sleeve which serves to return oil to the cooler. In level flight, one part of the unit, a 300-gph pump, returns oil through one of the cored passages in the main casting, then through a passage in the stator casting to the pump in the bottom of the intake casting. In climbs, the other part, a 90-gph gear pump, picks up the oil and feeds it into a common return line to the air-oil separator. Oil is returned from the main pump to the separator by a 300-gph pump driven by the same shaft as the delivery pumps.

Two types of fuel are used on the Jumo-004—gasoline for starting and J-2 brown coal crude for running. The gasoline is carried in the lower part of the annular tank set in the nose cowling and is automatically cut off after ignition at about 3,000 rpm. This is fed by an electrically driven pump delivering 90 gph at 28 psi. Near the end of World War II, centrifugal crude oil was also used as operating fuel.

The main single-stage, electrically driven, gear type of pump has a maximum delivery of 500 gph at 1,000 psi at 3,000 rpm.

Most interesting of the accessories is the all-speed governor, a 17-lb unit consisting basically of a centrifugal governor, oil pump, and spill-and-throttle valves. In operation, oil goes through a passage to the pilot piston and is distributed to outer faces of either the spill or the follow-up piston, depending on movement of the flyweights. Both pistons move at the same time, adjusting the fuel spill to counteract changes in engine speed. The distance between spill and follow-up pistons varies according to the flow of oil through the passages, so that the spill-piston

action is a step-by-step operation controlled by the follow-up, which returns to normal position after each step. A throttle valve is linked with the governor cam, so that when the throttle is advanced the fuel flow increases and response is immediate. The governor then takes over and adjusts the engine speed to a predetermined value set by the position of the cam.

THE BMW-003 TURBOJET [3]

Jet propulsion for aircraft had been studied by German scientists and engineers since the middle thirties, but practical application had to be postponed until flying speeds of at least 400 mph became a reality. Theoretical calculations indicated that this speed had to be attained before a tolerable thermal efficiency could be realized from a power plant of the jet-propulsion type; hence intensive development work on jet engines could not be undertaken until the speed requirement could be met. This condition was achieved by the Germans in 1938-1939 (Maj. Gen. Ernst Udet, 394 mph, June, 1938; F. Wendel, 469 mph, April, 1939), and development of jet propulsion was thereafter carried forward at a high priority upon instructions from the German Air Ministry (Reichsluftfahrtministeriums, known as RLM).

The Bavarian Motor Works (Bayerische Motoren Werke, or BMW) with its main plant at Munich, was Germany's leading air-cooled aircraft-engine builder. BMW's Spandau plant, near Berlin, had been investigating all types of aircraft propulsion system for many years; and upon receiving a directive from RLM to conduct intensive development work on turbojet engines, its efforts were concentrated on two specific types—the turbine-air jet (TL) unit and the motor-air (ML) jet unit.

The ML jet unit was similar to the power plant used by Campini in Italy, consisting of a conventional reciprocating engine driving a compressor instead of a propeller. The compressed air was heated by addition of fuel and expelled to the rear through a nozzle, thus producing a high-velocity discharge to develop thrust. Studies, supported by test data, indicated that in high-speed flight, TL and ML units were equally efficient. However, the TL unit—"turbojet," as it is known here—proved to be superior in simplicity of construction, weight, and size, whereas the ML power plant proved better in take-off thrust and specific fuel consumption under part load.

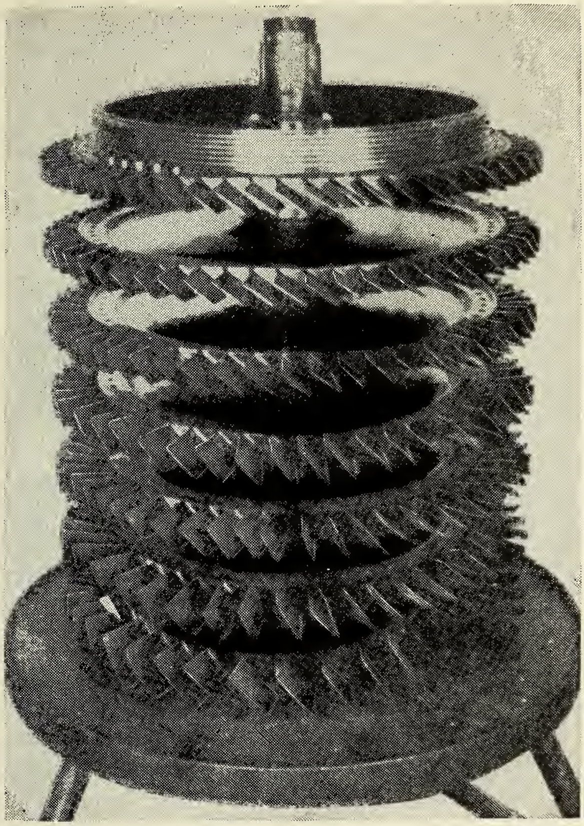
[3] Based on a design analysis by Maj. Rudolph C. Schulte, project officer, Turbojet and Gas Turbine Developments, Hdqrs., AAF, which appeared in *Aviation*, March, 1946.

In the light of experience available from the construction of gas turbines, and because of the simplicity of the complete power plant, BMW

Major Rudolph C. Schulte, gas-turbine project officer in the power plant section, Hdqrs. AAF, under General Chidlaw; member of the technical intelligence team at BMW works in Bavaria in early summer, 1945; gas-turbine installation engineer, CAA. (*Courtesy of Aviation.*)

gave preference to the turbojet. Eventually, the ML unit was discarded, since the development of the turbojet required full attention for early success.

In 1939, RLM requested construction of a jet plant with a thrust of 600 kg (1,320 lb) and a maximum diameter of 600 mm (23.6 in.). Specific output was based on preliminary calculations made by Messerschmitt and was intended to enable a twin-engine jet fighter plane to



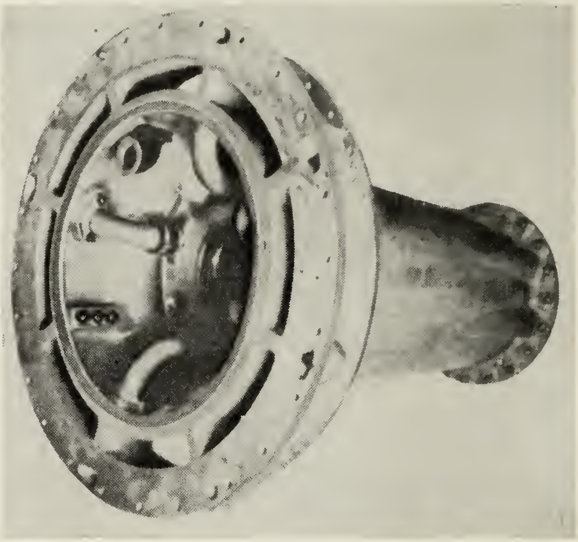
Seven-stage BMW-003 compressor mounted on work stand, with last compression stage at top. Note similarity to the Jumo-004 compressor. (*Courtesy of Aviation.*)

attain a speed of 850 kg per hr (527 mph). Accordingly, BMW started development of a unit called the "P-3302." It was decided at the outset to incorporate an axial compressor instead of a centrifugal-flow unit—the chief reason being that, with an axial-flow compressor, it was possible to build a power plant with smaller diameter.

Ten experimental power plants were to be built; and after preliminary testing of components and various configurations of turbine wheels, con-

struction of one was well under way by the end of 1940. The first experimental unit was run early in 1941, with a thrust of only 331 lb obtained. This discouragingly low output resulted from a number of causes.

The welded joint between the turbine wheel and turbine blading was far from perfect; hence, blade failures occurred at speeds as low as 8,000 rpm—whereas design speed was 9,000 rpm. Temperature distribution furnished by the combustion chamber was very uneven, causing pro-



BMW-003 turbine shaft-bearing support casting. (*Courtesy of Aviation.*)

nounced distortion of combustion-chamber inner liner, also of turbine-nozzle diaphragm, which in turn created friction at the turbine wheel. Pressure drop through the combustion chamber was much greater than anticipated. Combustion efficiency was very poor, large quantities of fuel remaining unburned after leaving the engine. Subsequent calculations showed that output of the compressor originally selected was too small for the turbine use, and major redesign of the compressor was necessary.

Test-Flown in 1941

The first flight test of this experimental unit was in late 1941, with two of the units attached to an Me-262, which, as a standby, had a conventional engine installed in the fuselage nose.

Because this first experimental power plant could not meet the requirement of a 600-kg thrust, it became necessary, early in 1942, to

design a unit that could handle a greater air-mass flow and still permit the utilization of previous experience. This redesign had to be done without changing principal dimensions and take-off behavior.

First test of the redesigned unit was conducted during the latter part of 1942, and a thrust of 550 kg was obtained, although many difficulties still remained. For example, fractures from vibration occurred in the blades at the first compressor stage after relatively short running periods. Starting characteristics of the new power plant were not so good as in the earlier unit. Efficiency of the compressor remained practically unchanged, whereas that of the turbine was greatly increased. Distribution of temperature in the combustion chamber was still far from satisfactory. Heat-induced brittleness was chiefly responsible for rather frequent turbine-blade fractures. And axial thrust bearings of the compressor frequently overheated because of oil starvation during the rapid acceleration interval in starting.

Most serious difficulties were sufficiently overcome by 1943 to commit this unit to production. The first production unit was known as "Series 0 109-003 A O," and the first flight with the BMW-003 was made in October, 1943, using a Ju-88 airplane as a flying-test bed.

Continued systematic improvement of all parts of the BMW-003—particularly the combustion chamber—resulted in a thrust of 800 kg (1,760 lb), and it was possible to make continuous runs of 20 and, later, 50 hr. This improved performance was attributed largely to the following factors: Vibration fractures in the compressor first stage were eliminated by use of heavier blading. A combustion chamber was designed that had a very low pressure drop and combustion efficiency of about 90 per cent. Even temperature distribution in the hot-gas upstream from the turbine-nozzle diaphragm was accomplished by incorporating air-mixing vanes in the combustion chamber. Friction thrust bearings were replaced by roller thrust bearings. Turbine blades were made of hollow sheet metal and air-cooled. And the thrust nozzle was made adjustable, with air cooling provided for the adjusting gear.

By August, 1944, BMW had delivered its first hundred BMW-003 turbojets. In September, 1944, a 42,000-ft altitude was reached by an Arado-234 equipped with these power plants. By April, 1945, the BMW-003 unit was well along in production and incorporated many improvements that added to reliability of performance as well as to simplification of manufacture. (Fuel shortages in the Reich became so severe that by early 1945 it was necessary to burn a crude fuel, known as J-2, similar to Diesel oil, thus making necessary major modifications in the

fuel system.) Seven hundred fifty units were produced before the onrush of the Allied armies caused all work to be stopped.

Development of Major Components

Major components of the BMW-003 consist of an inlet duct that guides ram air into the compressor; a seven-stage axial-flow compressor serving to compress this air to about 3.5 atm; an annular combustion chamber, containing 16 fuel nozzles, where compressed air is heated by the combustion of fuel; a turbine assembly, consisting of turbine nozzles and turbine wheel, which drives the compressor and accessories; and an adjustable tail cone located aft of the turbine, providing desired thrust at all times while maintaining temperature of gases at turbine wheel below maximum allowable.

INLET DUCT. Early experimental units were equipped with inlet ducts conforming to Association of German Engineers (Verein Deutscher Ingenieure, or VDI) standards, having a slight increase in local air velocity at outer contours so as to make distribution of velocity as uniform as possible prior to entry of air into the compressor. Subsequent tests soon indicated that a more accurate aerodynamic form was required at the air inlet if the unit was to meet the various take-off and flight conditions in a satisfactory manner. For example, for flight conditions, an inlet form was required that would have least possible increase in local velocity of air at the outer contour so that flow separation would be prevented during high-speed flight. Furthermore, for conversion efficiency in the diffuser—*i.e.*, at high flying speeds—conversion of ram air into dynamic pressure ahead of the compressor must be as favorable as possible. For take-off, it was important to prevent flow separation at the entrance of the duct, since this separation has a marked effect on ram efficiency, and any reduction in the latter would decrease thrust output, resulting in longer take-off runs.

Sheet Metal Used

The air intake is constructed of light alloy sheet. Internal diameter increases from nose cowl to the compressor intake, smallest diameter being 14.8 in.

Around the air intake are mounted an oil tank, oil cooler, and small fuel tank for the Riedel starter. The oil tank occupies the topmost position, whereas the starter fuel tank is immediately behind the oil tank, and the oil cooler occupies half the outer circumference of the air intake, being located mainly on the left side. Air through the cooler is caused

Table II. *Gas-turbine Units Developed by BMW*

Model designation	*Description*	*Weight, lb; and diam, in.*	*Performance*
BMW-109-003A and C	7-stage axial-flow compressor; single-stage turbine; annular combustion chamber; 16 fuel nozzles; adjustable tail cone	Wt, 1,342 Diam, 27.1 L, 124	Static sea-level thrust, 1,760 lb at 9,500 rpm and 1,980 lb at 9,800 rpm. For BMW-003A: 560 mph at sea level, 1,555 lb thrust, 560 mph at 32,000 ft, 695 lb. Sfc, 1.47-1.40
BMW-109-003D . . .	8-stage axial-flow compressor; 2-stage turbine; annular combustion chamber; 16 fuel nozzles; adjustable tail cone	Wt, 1,430 Diam, 27.1 L, 124	Static sea-level thrust, 2,420 lb at 10,000 rpm. Sfc, 1.10
BMW-109-003R . . .	Consists of BMW-003A through D gas turbine plus rocket of 2,750 lb thrust		
BMW-109-018	12-stage axial-flow compressor; 3-stage turbine; annular combustion chamber; adjustable tail cone; compression pressure, 7 atm	Wt, 5,060 Diam, 49.3 L, 165	Static sea-level thrust, 7,500 lb at 6,000 rpm. At 560 mph at sea level, 6,650 lb. At 560 mph at 32,000 ft, 3,220 lb. Sfc, 1.1-1.3
BMW-109-028	Modification of BMW-018 having 4-stage turbine and driving contrarotating propellers	Wt, 7,270 Diam, 49.3 L, 228	Static sea-level thrust, 4,850 lb + 4,700 bhp Total eq bhp, 6,570. At 500 mph at sea-level, 3,140 lb thrust + 7,000 bhp Total eq 12,600 bhp. At 500 mph at 32,000 ft, 1,710 lb thrust plus 3,280 bhp Total eq bhp, 6,800

to flow in a reverse direction to the compressor air by providing scoops halfway along the internal wall of the intake. Air enters these scoops, passes forward through the cooler, and joins the main air stream again through an annular slot formed between the nose cowling and the air-intake wall.

Compressors. Extensive tests were carried forward on axial-flow compressor designs by the Experimental Institute of Aerodynamics at Göttingen. In 1939, this laboratory developed model compressors which showed an average efficiency of 80 per cent. Blade velocity of this compressor at the outside diameter was 820 fps, and axial velocity of air flow was 328 fps. A compressor similar to this test model was designed for the first BMW experimental units. Blading was arranged in such a way that pressure conversion took place in the rotating blades, and the stator blades served merely for deflection. Profile of the rotating blades was based on a high-speed profile developed at Göttingen for fairly high Mach numbers. When tested on the stand, the compressor showed efficiencies of 80 per cent over a wide range of loads. However, as previously stated, the unit proved to have insufficient capacity for the output specified by RLM.

Hence, a new design of greater capacity, but with the same diameter, had to be made. With cooperation of other sources, BMW constructed a compressor with a 30 per cent increase in capacity. Number of stages was increased from six to seven, average air velocity was increased to 460 fps, and rated rpm of the unit raised from 9,000 to 9,500. Pressure conversion no longer took place entirely in the rotating blades, but 30 per cent of this pressure rise was accomplished by using guide, or stationary, blades. NACA profiles were used for the rotating blades, whereas arc-shaped profiles were chosen for stationary blades.

During early test runs of the new unit, vibration failures occurred in the first compressor stage after 20 hr or less—usually resulting in complete destruction of the compressor. Cause of these failures was found in the supporting profiles of the casing mounted ahead of the compressor. Decreasing their number and diminishing the profile thickness, as well as changing the angular position of the rotating blades in the first stage, made some improvement. However, only by changing the form of the blades in the first stage—increasing thickness of the base to 12½ per cent of profile length and reducing the outer end to 5 per cent—was it possible to eliminate vibration fractures. Although 2 per cent in compressor efficiency was lost by this modification, the unit had longer life, and efficiencies were fairly constant under various load conditions.

The compressor of the first BMW-003 model released for mass production had magnesium or electron blades for the first three stages, and the last four (higher) pressure stages were made of dural. Blades were dovetailed to the compressor disks and pinned by one hollow rivet per blade. Compressor disks were made of aluminum alloy dipped in lacquer (for corrosion protection) and were provided with steel bushings to prevent damage to the bore through frequent disassembly. The compressor shaft was made of tempered-steel material, and the compressor casing was cast from magnesium alloy. Pressure ratio at 9,500 rpm and 42 lb of air per second mass flow was a little over 3:1, under no ram conditions. At 560 mph, this ratio increased to about 3.9:1. Static, or zero, ram pressure of 3 is somewhat low for a seven-stage compressor; however, the blades had a fairly flat camber. Design Mach number of blades was 0.8.

COMBUSTION CHAMBER. When development work on turbojets first started at BMW, little was known concerning shape, size, and general construction of a combustion chamber that would be capable of handling such a large volume of air at such high velocities and still give stable burning. Many configurations were tried.

One of the first facts learned was that an eddy area was required somewhere in the air stream to maintain combustion under the high-velocity flow conditions. In the first burner, immediately downstream from the compressor exit, 16 fuel nozzles were evenly distributed about the periphery and sprayed fuel into a conically widened circular space. The fuel spray formed a cone and struck upon a circular plate, and eddies developed just behind this plate, in which combustion could be started and maintained. However, this design presented several disadvantages. Air coming from the compressor struck the eddying plates unevenly, causing uneven temperature distribution behind the burner. Air flow could not be maintained constant, and flames would break off prematurely. Also, the plates themselves were of ceramic material and frequently broke. To improve the flow to the eddy plates, conical intake ports were installed so that each plate received the proper portion of air, and plates were fabricated from steel instead of ceramic material.

Combustion was substantially improved, and full-load rpm could now be attained. However, the temperature distribution was still unsatisfactory, and several modifications of the burner were attempted. Further testing showed that injection of the fuel into the eddy area was improper, since the finely atomized spray would change into fairly large droplets upon striking the plate. Other parts of the fuel spray, unaffected by the eddy area, passed through the combustion chamber unburned, since heat-

ing of cold particles of air under conditions of improper temperature distribution occurred either too late or not at all.

Hence, eddy plates were replaced by conical eddy-producing elements with the fuel nozzles ejecting directly into the eddy area of the elements, and this system was used in the production engines. To make the flow to the burner as favorable as possible, the eddy producers were constructed in the shape of a ring, resulting in an air flow similar to that associated with aircraft engine cowling. Combustion chambers of this type showed efficiencies of 90 to 95 per cent for full-load operation.

It was also found that the combustion cone and air-conducting tube could be developed as an independent element of the combustion chamber—a substantial operational improvement, since these burners could be easily and rapidly removed for cleaning or for replacement in event of damage.

Satisfactory tests of the conical burner also settled the controversial question of whether combustion in a chamber with individual burners (annular type) is superior to combustion in several individual chambers —the results clearly indicating that the annular type of chamber was the more satisfactory. Construction and mounting are much simpler, and difficult transitions from compressor to combustion chamber and from the latter to the turbine are eliminated. Moreover, to improve distribution of temperature, it was decided, on the basis of thorough preliminary tests, to substitute the partial-combustion process for total combustion.

Pressure loss in the combustion chamber plays an important part in the over-all efficiency of the unit. This loss is caused by (1) pressure decrease in the burners resulting from warping of liners and other protruding surfaces, causing disturbance in the air flow; and (2) diminished pressure resulting from heating of the gas in a combustion chamber of constant cross section—a less important effect. As a result of continued systematic development efforts, BMW was able to design and construct a combustion chamber that had low pressure loss yet had a sufficient margin to ensure stable combustion.

After leaving the compressor, the air is divided into two streams—primary and secondary. Primary air stream passes through the burner and provides the oxygen to burn the injected fuel. By means of special mixing fin elements, secondary air is introduced into the hot gas stream at a specified point downstream from the burners. This secondary air serves to lower the temperature of the gas sufficiently to meet the turbine-inlet temperature requirements and also to maintain uniform temperature at the end of the combustion chamber, thus eliminating hot spots. From

a structural standpoint, the ratio of primary to secondary air is determined essentially by the free passage areas at the burner end and at the mixing fins. It can be adjusted by varying the appropriate passage areas until the desired result is obtained. With this combustion-chamber configuration, it proved possible to reduce the ratio between maximum and mean temperature of the hot gas to 1.2, as against 1.8 to 2.0 for earlier designs.

The annular combustion chamber incorporates 16 fuel-injection nozzles, each having an eddy-producing conical element around the nozzle tip and 80 mixing fins divided evenly between inner and outer rings.

The forward section of the combustion chamber, which carries the fuel nozzles and conical eddy-producing elements, is made of sand-cast aluminum alloy. Combustion-chamber liners are made of 1,010 steel and protected against fusion by an aluminum lacquer burned in at a temperature of 400°C. Mixing fins were in a much hotter zone and were constructed of a better heat-resisting alloy, known as "Sicromal," possessing a high chromium content and containing silicon and aluminum to improve its heat-resisting properties.

Turbine. This unit was considered of primary importance, the following requirements being specified: (1) The turbine must be able to operate satisfactorily at high temperatures, to secure maximum efficiency from the complete power plant; (2) a large flow of air must be handled by a wheel of smallest possible diameter; and (3) the number of stages must be maintained as low as possible.

To expedite this development, BMW purposely confined its investigations to a one-stage type of turbine construction. It was decided to design a unit with an average blade speed (at center of blade) of 820 fps and a working temperature of 800°C (1472°F) in front of the turbine. The turbine wheel for the experimental units had a mean diameter of 20.8 in. and a blade length of 3.52 in. and revolved at 9,000 rpm. Early-design blades were hollow and consisted of two pieces of sheet metal welded together, and the blade was also welded to the wheel. However, the quality of the weld could not be relied upon; hence, it was necessary to attach the blade to the wheel by mechanical means. Forged blades gave much longer life; but because of fabrication difficulties, they could not be adapted to mass production and were discarded in favor of an air-cooled sheet-metal blade of improved design.

The hollow, sheet-metal, air-cooled turbine blade used in production was made from a chrome-nickel alloy. The alloy was cut in long sections having a width approximately that of the blade height, and the strip was

then taper-rolled to a thickness of 2.7 mm on one end and 0.6 mm at the other, cut to proper length, bent in a die, and folded over. The trailing edge was welded by the atomic-hydrogen process.

Ten additional operations finished the blade, with cooling insert. The blade was attached to the turbine wheel with dowels and wedges, so that centrifugal pressure from the rotation of the wheel held the bucket firmly in place.

The flow of cooling air used on the turbine wheel and buckets amounted to approximately 1 per cent of the total air flow through the unit. The turbine wheel was made of a chrome-molybdenum alloy; but, to conserve critical materials, it was found that by use of air cooling, an inferior alloy could be substituted. After turbine blades were in place, a thin sheet-metal disk was placed on each side of the turbine wheel. Cooling air was introduced between these disks and the wheel, from a point near the turbine axle, and was exhausted through the turbine buckets, thus cooling them as well.

Turbine-nozzle Diaphragm. At first, the turbine-nozzle blades were made simply of twisted sheet metal (as is the practice with turbosuperchargers) passed through an opening in the outer ring and welded to the inner ring. These vanes soon become badly distorted, and sheet-metal profiled vanes, air-cooled from the inside, were introduced, distortion being eliminated when the cooling air was made to exhaust through the trailing edge of each blade. However, vibration fractures often occurred at the point where the blades were welded to the nozzle ring, and this difficulty had not been entirely overcome when production ceased as a result of American occupation.

Thrust Nozzle. Tests on early experimental engines were carried on with stationary thrust nozzles. This simplified construction, and the exhaust outlet area could be made exactly as desired. It was soon evident that, to control the temperature of the gas at the turbine inlet—a critical point—under various conditions of flight and engine output, it was extremely desirable to control the thrust-nozzle area by having a movable, streamlined "bullet" in the exhaust cone.

Distortion occurred in the bullet, and failures from overheating occurred in the rack and pinion moving the bullet in and out. An improved design was adopted to remedy these difficulties, with the conical mushroom, or bullet element, moving in and out, and the regulating mechanism air-cooled to ensure free operation. Total distance traveled by the bullet element was 4.2 in., which changed the thrust-nozzle area from 155 to 220 sq in.

The thrust nozzle was made of deep-drawn 1,010 sheet metal. After fabrication by spot welding, the entire assembly was sprayed or dipped in aluminum lacquer and baked at a temperature of 400°C.

Auxiliary Drives and Reduction Gearing. On the production unit, the gears are mounted in a casing situated between the starter engine and the front of the compressor shaft. This casing contains a complicated drive system between starter and compressor shaft and compressor shaft and auxiliaries. There are two extension shafts on the same axis between compressor shaft and starter dog. The forward shaft carries the starter dog, which meshes with the starter engine dog; and the drive is taken by a short offset stub shaft to the compressor shaft. The other extension shaft, which revolves independently of the starter shaft, drives the auxiliary bevel gear wheels from the compressor shaft.

Three auxiliary drives are taken from the internal bevel gears to the outside of the main casing by splined shafts. The top vertical shaft provides the drive to the main auxiliary gearbox on top of the unit. Fuel pump, governor, fuel regulator, and tachometer are mounted on this gearbox. The lower vertical drive connects with the front oil-scavenge pump. The horizontal shaft drives the oil-pressure pump, located on the right side of the unit.

The development program for the major components of the BMW-003 turbojet was by no means completed; but because of the urgency of getting this unit ready for combat, many plans for improvement had to be shelved. Continuous running of 50 hr could be accomplished before overhaul was necessary, and this was considered sufficient to meet combat requirements specified by the military.

Selection of materials for the turbojet was difficult and entailed frequent changing, because elements so necessary for heat-resistant alloys were very scarce and, toward the end of the war, were not available. Yet, despite substitution of materials, very little depreciation in physical properties was evident.

Starting the Turbojet

The BMW-003 is started with a small, compact, air-cooled, two-cycle, two-cylinder gasoline engine. Manufactured by Riedel, the unit is mounted at the forward end of the compressor within the inlet duct and is completely enclosed by a paraboloid-shaped hood or cowl. The engine operates at very high speed and can run for only a short time before overheating; but since it takes less than 1 min to complete the starting procedure of the turbojet, operation need not be to a point of overheating under

normal starting conditions. Design of the centrifugal clutch, starter-dog engaging mechanism, carburetion, and electric starting assembly is rather ingenious. The Riedel engine burns aviation gasoline to which is added a small amount of lubricating oil.

As previously stated, the BMW-003 operates on J-2, a crude Diesel fuel; but it cannot be started with this fuel; hence, it is necessary to carry a small tank containing aviation gasoline for starting. The gasoline is injected into the combustion chamber by 6 fuel nozzles, which are distinct from the 16 nozzles used for injection of the J-2 operating fuel. Starting-fuel nozzles are located in the forward section of the combustion chamber, equally spaced between main nozzles. Two topmost nozzles spray directly upon the two spark plugs; and upon ignition, the flame rapidly jumps from these two ignition cones to the other four nozzles. When the main fuel nozzles are put into operation, ignition through the entire combustion chamber is rapid and uniform. Current for the spark plugs is furnished by a 24-v battery through a buzzer and ignition coil housed in a box fastened to the compressor casing.

Starting procedure is as follows: The starting engine is primed by closing the electric primer switch; then ignition of the turbojet and ignition and electric starting motor of the Riedel engine are turned on (this engine can also be started manually by pulling a cable). After the Riedel unit has reached a speed of about 300 rpm, it automatically engages the compressor shaft of the turbojet. At about 800 rpm of the starting engine, the starting-fuel pump is turned on; and at 1,200 rpm, the main (J-2) fuel is turned on. The starter engine is kept engaged until the turbojet attains 2,000 rpm, at which the starter engine and starting fuel are turned off, the turbojet rapidly accelerating to a rated speed of 9,500 rpm on the J-2 fuel. During acceleration, the pilot must observe closely the functioning of the governor, also the temperature of the hot gas in the thrust nozzle, which must not exceed 750°C.

Jet Control

The object of jet control is to coordinate the three principal variables—turbine rpm, fuel flow, and exhaust-nozzle area—so that optimum efficiency may be obtained at all altitudes without exceeding maximum allowable turbine-blade temperature. For this purpose, fuel flow and rpm are integrated by a constant-speed governor. Strength of the control spring in the governor depends on the throttle position. A special accelerator valve allows for the inertia of the turbine and compressor when the throttle is opened too rapidly or abruptly.

When the pilot opens the throttle too fast, an aneroid, controlled by the pressure difference across the compressor, opens a by-pass for the excess fuel until a predetermined rpm is reached. This method precludes an overrich mixture during initial acceleration, thus avoiding overheating. Since faulty operation would lead to serious overheating of the turbine, a safety device is included to connect the throttle linkage to the exhaust-nozzle-area control mechanism, so that a progressive opening of the throttle for climb automatically closes the exit to the appropriate position. This operates in the opposite fashion when the throttle is closed for landing or shutdown.

The exhaust-nozzle area has these manual controls: position *A*, starting and idling, largest opening (186 sq in.); position *S*, intermediate position for climb (155 sq in.); position *F*, high-speed flight position (147 sq in.); and position *H*, high-altitude flight position (163 sq in.).

Fuel System

Fuel flows from the tanks through a low-pressure filter to the Barmag high-pressure gear-injection pump and then through a high-pressure filter to the governor, equipped with a centrifugal pendulum that meters fuel through a spill valve to maintain the speed desired. The governor cuts in at 6,300 rpm and controls the speed up to 9,500 rpm. Below this speed range, the unit is controlled manually by the pilot's throttle. From the governor, fuel flows through a manifold to the 16 nozzles, where it enters the combustion chamber in a finely atomized spray. Under full-load conditions, fuel-injection pressure is 30 atm abs, with a nozzle bore of 1.0 mm; and 55 atm abs, with a nozzle bore of 0.6 mm.

Oil System

A mixture of 60 per cent lubricating oil S3 and 40 per cent spindle oil used in the oil system is stored in a 25-liter tank located on top of the unit in the rear of the inlet duct. Normal operating pressure is about 5 to 6 atm at a temperature between 10 and 90°C.

From the oil tank, lubricating oil flows to a gear pressure pump and through a filter into a manifold. These accessories are attached to the forward part of the compressor casing. From the manifold, branch lines lead to the governor and oil-pressure gauge. The main oil line from the manifold is, in turn, divided into two branches—one leading to the forward part of the compressor to lubricate the compressor thrust bearing and accessory gear trains; the other leading to the rear compressor-bear-

ing support to feed the rear compressor bearing as well as forward and rear turbine shaft bearings. Separate lines lead to the injection pump, generator, and air-compressor drives.

Two scavenger pumps are provided—one under the rear compressor support, the other under the forward part of the compressor casing. These pumps return scavenged oil to the tank through an oil cooler located just to the rear of the inlet duct. A by-pass is provided that shunts the oil cooler when the oil is congealed or too thick to pass through the cooler. Air vents and an oil separator are also provided.

THE BMW-109-003R TURBOJET

In an attempt to combat Allied bombing, the Luftwaffe made frantic requests for an interceptor fighter that had the rate of climb of a rocket plane yet could maintain the endurance of a turbojet fighter. BMW therefore developed the BWM-003R. This propulsion unit consisted of a conventional BMW-003A, C, or D turbojet of 1,760 to 2,420 lb static sea-level thrust, on which was mounted a rocket using a liquid propellant for delivering a thrust of 2,750 lb; and two of these modified units were tested in an Me-262. This plane carried a sufficient amount of propellants to give the rocket an endurance of 2 min. The rocket—which could be turned off and on at the discretion of the pilot—was not intended for use during take-off but only when a very rapid climb was desired or for quick bursts of acceleration during level flight. Sufficient turbojet fuel was carried to give an endurance of 20 min at sea level or 60 min at 30,000 ft. According to the German engineers, the performance achieved was sensational.

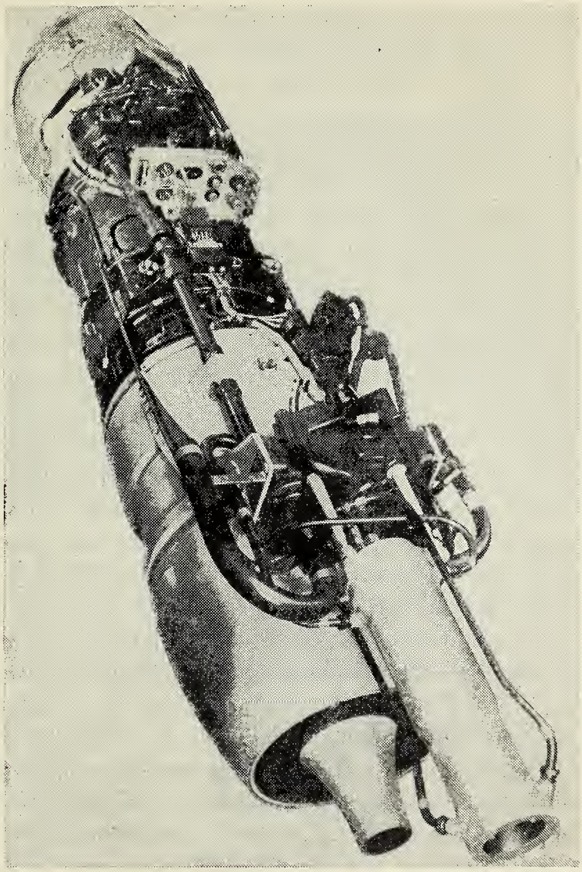
With reference to the chart showing rate of climb of craft equipped with BMW-003R units, it can be seen that when a climb is started from sea level with both turbojets and rockets in operation, as in curve *A*, a height of 9 km (27,600 ft) can be reached in 2 min, at which point the rocket propellant is expended. The plane climbs an additional kilometer through combination of inertia and the turbojets and then continues on to the 11-km (36,000-ft) ceiling with turbojets alone.

The craft has thus attained high flying speed and high altitude with expenditure of very little turbojet fuel. Since fuel consumption for turbojets is most efficient at high altitude, maximum range can be obtained by this method. Curve *B* shows a climb using turbojets only.

If enemy craft is sighted at a higher level, the rockets can be turned on at any intermediate altitude for a rapid climb to intercept. Because

of heavy blows from Allied bombing, very little service testing could be accomplished on this combination unit; hence it was never placed in combat use by the Germans.

Several improved versions of the BMW-003 were in various stages of development during the closing stages of action in the European theater.



BMW-003R unit, a conventional 003A, C, or D, with rocket unit added. Rocket unit was not used for take-off, but for added speed bursts or extra climb at high altitudes. (*Courtesy of Aviation.*)

For the most part, improvements were intended to increase reliability of operation. Unit BMW-003D was a completely new design, having a 30 per cent increase over the BMW-003A in air-mass flow. The BMW-003D was designed for an eight-stage axial-flow compressor and two-stage turbine. Its design thrust was 2,500 lb at take-off. Yet, with these improve-

ments, principal dimensions and weights remained essentially the same as those of the BMW-003A.

A much larger turbojet, the BMW-018, with 12-stage axial-flow compressor, three-stage turbine, and a compression ratio of 7:1, was designed in early 1944. This unit was intended to operate at altitudes up to 50,000 ft and with a sea-level thrust of 7,500 lb at 6,000 rpm. However, only the compressor was fabricated; and finally the project was dropped in December, 1944, since damaging Allied bombing raids made it obvious that this engine could not be completed in time for effective use. Later, the compressor was destroyed to prevent capture.

Examination of the wreckage revealed a very light construction. The first five disks of the rotating blades were of dural, and the remaining seven of steel. Blades were secured to the first seven stages by hollow rivets. The compressor rotor was supported on two ball thrust bearings at the turbine end and a single roller bearing at the forward end.

Design of the annular combustion chamber of the BMW-018 was similar to that of the BMW-003 but called for 24 fuel-injection nozzles and 8 auxiliary injection nozzles for starting. The turbine has not been constructed, but drawings showed the turbine shaft to be supported by a single roller bearing at the rear of the turbine disk. The front end was supported in a spherical seat within the compressor shaft, and an internal tie rod was planned for transferring thrust to the forward end of the compressor shaft. It was planned to route cooling air from the fifth stage of the compressor to the turbine blades, through the hollow turbine shaft. For cooling the turbine guide vanes, it was planned to bleed air from the last stage and pass it through the annular space between the combustion chamber and its housing. The drawing indicated a three-stage turbine.

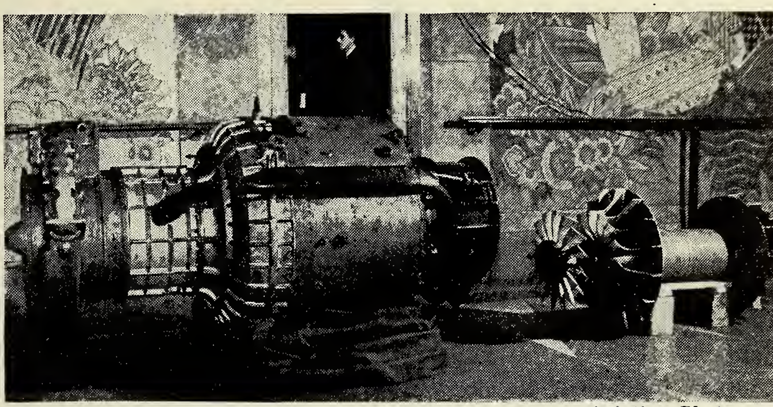
Another turbojet was designed to drive a dual rotating propeller. This design—the BMW-028—had a BMW-018 compressor but included an additional, or fourth, stage added to the turbine. Because of the adverse turn of the war, this unit could not be built. Details on design performance of both the BMW-018 and the BMW-028, as well as for various models of the BMW-003, are shown in our table of descriptive data for BMW gas-turbine developments.

At the time of Germany's defeat, accelerated service testing of the BMW-003 engines was being conducted, employing the Heinkel He-162, Arado Ar-234B and C, Junkers Ju-287, and Messerschmitt Me-262.

THE HEINKEL-HIRTH 109-011 A-O TURBOJET

Nearing the production stage at the end of World War II was one of the most interesting of the German jet-propulsion projects—the He-109-011 A-O, first known in this country as the "Heinkel-Hirth 011."

Analysis of Air Material Command translations of captured German documents shows that it is not quite either a true centrifugal or a true axial-flow engine, for its compressor has a front single-stage axial-blade



Aviation Photograph

Heinkel He-S8A, one of the Germans' first attempts at jet propulsion by gas turbine, a project started in secrecy well before the war. This model never successfully powered a plane but made some flights on a conventional plane serving as a flying test bed.

row followed by a diagonal compressor, then a conventional three-stage axial-flow unit, all on the same shaft.

The double-skinned air-intake hood serves to straighten the air flow for the first compression stage; to house the accessories, oil tank, and pumps; and to support the front of the engine cowling. The Germans had designed both warm-air and electric-heating methods for the leading edge of the hood to prevent icing.

As the air leaves the first axial stage, the annular passage is narrowed by a fairing around the shaft which is attached to the diagonal compressor, the blades of which are of much greater chord than those of the other compressor stages.

Compressor stator blades are used only in the final axial stages—one row each between the blade rows and three rows downstream from the final compression stage.

In the annular combustion chamber, most of the air is divided into two

flows by an annular headpiece, with a small portion going into the headpiece for mixture preparation and combustion.

Most of the air is led through two outside and inside rows of vanes at the end of the combustion chamber into the mixing chamber to attain the required temperature. The housing wall around the combustion chamber is protected against radiant heat by an annular insulator around which is circulated fresh air from the chamber.

Fuel is fed into the combustion chamber by 16 injection nozzles equally spaced around the perimeter. Four ignition plugs—two on the lateral axis and two 45 deg upward—are set in the same plane as the fuel nozzles, and provision has been made for installation of two additional ignition plugs 45 deg down from the lateral axis. The ignition sets consist of injection nozzles and special spark plugs.

The two rows of hollow turbine-nozzle vanes are cooled by air bled off through an annulus just aft of the final compression stage, this air being ducted between the combustion chamber and the rotor shaft, which is shielded by an annular insert.

The two-stage turbine is also cooled by the air bleed from the compressor. Both disks have hollow, pot-shaped vanes, the air being brought to the second stage through holes bored in the first stage. In both stages, the air goes out through the blades.

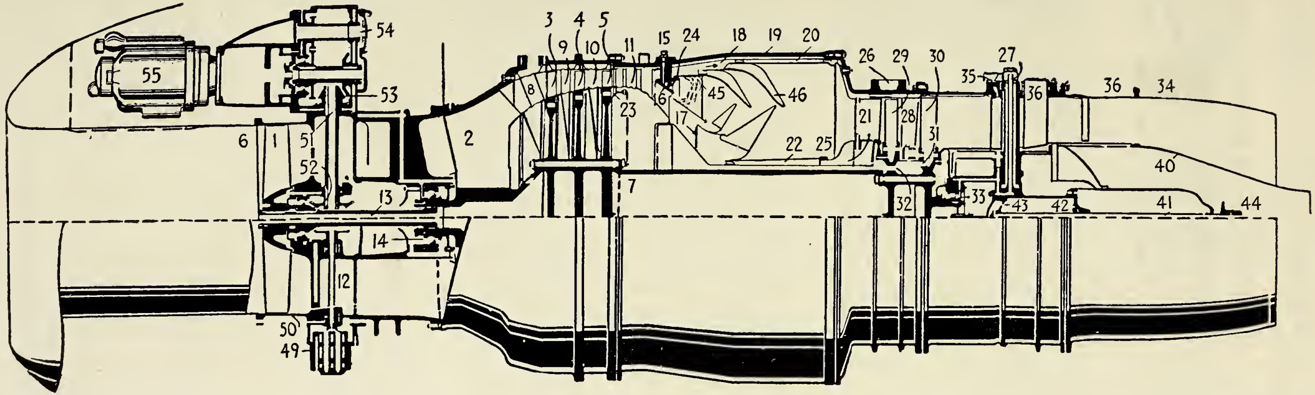
An adjustable tail-cone bullet, similar to that used on the BMW-003, is moved by a piston inside the cone. Originally, the He-011 design called for adjustment of the bullet by throttle control, to control feed and drain pressure oil pipe; but this was later changed to an electrically connectable magnetic cross-feed valve independent of the pilot rods. It is connected so that, when switched off (line without power), it moves the bullet to operating or extended position and, when switched on, brings it to starting or retracted position.

The front main ball bearing, which takes the axial thrust, is set just ahead of the diagonal compressor. A floating rod extends forward from it to drive the front axial compressor and, through bevel gears and shafts, the accessories. The rear bearing, set just aft of the turbine, is cooled as well as lubricated by oil under pressure.

Accessories, located atop the engine, include a Riedel starter similar to that used on the Junkers Jumo-004 and BMW-003 turbojets, a Bosch or Seimens generator, Barmag pump, Knorr air compressor, and tachometer.

The fuel system is controlled by the pilot's throttle, which operates a Junkers constant-speed governor to control supply and, thus, engine speed.

Fuel goes from the tank through a filter to a Graetz low-pressure pump —a double-gear unit with two suction sides independent of each other



(1) Front axial rotor; (2) diagonal rotor; (3, 4, 5) third, fourth, fifth rotors; (6) air-intake hood; (7) main shaft; (8, 9, 10) guide grids; (11) triple grid; (12) pump drive shaft; (13) floating rod; (14) front main bearing; (15) connection for fuel pipe; (16) arrow-shaped ring (nozzle ring); (17, 18) air flows between compressor and turbine; (19) housing wall; (20) circular chamber; (21) guide grip in front of turbine wheel; (22) circular chamber; (23) annular cool-air gap; (24) injection nozzles; (25) cool-air passage to guide grids; (26) fastening flange; (27) connection for lubricant pipe; (28) guide grids between turbine rotors; (29, 30) turbine rotors; (31) cool-air holes; (32) cool-air holes; (33) rear main bearing; (34) thrust-nozzle housing; (35) cool-air connection; (36) ventilation tube; (37) pressure-measurement place; (38) (not shown—not identified); (40) thrust-nozzle sleeve; (41) piston rod; (42) pressure cylinder; (43) piston; (44) piston-rod bearing; (45) mixers; (46) scoops; (47, 48) (not shown—not identified); (49) lubricant pump set; (50) front compressor housing; (51) vertical shaft; (52, 53) bevel gears; (54) drive connection for turbine's extension shaft; (55) starter

Cutaway drawing of the 109-011 turbojet (originally known here as the Heinkel-Hirth 011) which the Germans had nearly completed when they surrendered. Unusual is use of front axial compressor (1), diagonal rotor (2), and three-stage axial-flow compressor (3, 4, 5).

as well as a pressure side and a circulation volume of approximately 792 gpm for each pump side.

From the delivery side of the pump, the fuel is fed to the Barmag high-pressure pump having an output of about 820 gpm at approximately 90 psi. Excess fuel delivered by the low-pressure pump is diverted by the high-pressure unit and led back to the low-pressure suction side by an overflow spring valve.

The high-pressure pump fuel is delivered to the governor, from which two annular pipes feed to 16 fuel-injection nozzles in the combustion chambers. A pressure valve in one of the annular pipes prohibits fuel from entering the combustion chambers without reaching the pressure necessary for operation.

Lubricating-oil tanks of 12.6 qt capacity are on the lower part of the accessory support on either side of the pump set, which consists of a delivery and two return units. An additional return pump is set behind the rear bearing.

Oil is gravity-fed from the tanks to the delivery pump, which sends it through a filter to a collector. Circulation is at a rate of 9.24 gpm. All bearings in the accessory case and the two main bearings are lubricated by the collector, which is under operating pressure, through two distributor pipes. Gears and the bearings of the front axial compressor are centrifugally lubricated; the bevel gears are spray-lubricated.

Oil from the gear case runs back into the tank; that from the bevel gears is drawn off by one of the two return pumps, the other drawing used oil from the front main bearing. Oil to operate the tail-cone bullet is taken from behind the filter by the governor pump and led again into circulation for cooling.

101-11 *A-O Specifications and Data*

Thrust, static sea level at 10,200 rpm	2,860 lb
Maximum rpm	11,000
Idling rpm	6,000
Starting rpm	3,000
Length, bullet retracted	131.6 in.
Length, bullet extended	138.1 in.
Maximum diameter (at combustion chamber)	34.4 in.
Dry weight (without accessories)	1,973.1 lb
Accessory weight	112.1 lb
Total dry weight	2,085.2 lb
Exhaust-gas temperature (mid-jet at nozzle)	1472°F
Exhaust-gas temperature (at nozzle rim)	932°F
Exhaust-gas temperature (mid-jet, 6.5 ft from nozzle)	1092-1380°F

CHAPTER THREE

The British Were Early, Too

British aircraft gas-turbine developments have proceeded along two distinct and largely independent lines. The first was the research work on axial compressors by Dr. A. A. Griffith, when he was head of the Royal Aircraft Establishment (RAE) engine department; and by H. Constant, first assistant to Dr. Griffith and later his successor. The other development line, better known to the world, is associated with the name of Air Commodore Frank Whittle and his work on centrifugal-compressor gas turbines.

Historically, the axial-flow type came first. In 1926, Dr. Griffith produced at the RAE an aerodynamic theory of turbine design based on flows past airfoils instead of through passages. The British Air Ministry and the Aeronautical Research Committee agreed to preliminary research, and work began in 1927. Results of the various sets of experiments and tests were encouraging and are still of use to turbine designers.

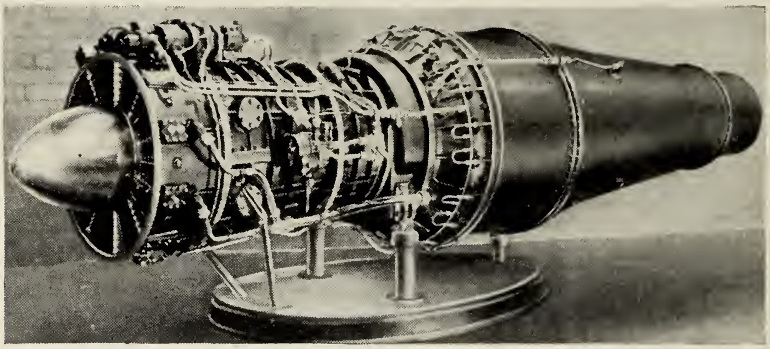
In November, 1929, Dr. Griffith gave in an official paper the prospects of an internal-combustion turbine driving a propeller. He concluded that it would be lighter, smaller, and more efficient than a piston engine, a conclusion that has been fully verified in operational units developed within the past few years.

His scheme was based on a contrarotation turbocompressor; but no work was carried out on it until 1938, when the turbocompressor was designed at the RAE, built by Armstrong-Siddeley in 1939, and run in 1940. It was christened *Anne* and had eight stages of free vortex blading of 6-in. diameter. The initial test proved a failure, because of a faulty oil seal; but a second compressor with larger blade clearance was built and successfully tested. In the meantime, in 1936, an axial-flow compressor was designed at the RAE, the unit being completed in 1938.

In March, 1937, Constant presented a paper on an internal-combustion turbine driving an aircraft propeller, advancing in certain particulars the ideas previously expressed by Dr. Griffith. He concluded that such a unit could have as good performance as, or better performance than, the current piston engines, on a basis of weight and fuel economy, except when near the ground. He pointed out that developments in heat-resistant

materials and in compression design would increase the superiority of the turbine, and he stressed its simplicity.

The Air Ministry authorized the work to proceed, asking Metropolitan-Vickers to collaborate; and a decision was reached to design a power plant having a low-pressure axial compressor driven by a low-pressure turbine in series with a high-pressure compressor driven by a high-pressure turbine and with a separate power turbine. Only the high-pressure part of this unit was built, and it became known as the "B10." Performance during the tests beginning in December, 1940, was remarkable.



First British axial-flow turbojet to fly was the Metropolitan-Vickers F2, with a nine-stage axial compressor, single annular-combustion chamber, and two-stage turbine. Test-flown in a modified Meteor on Nov. 13, 1943. Above is the F2/4 version.

Early in 1939, C. and A. Parsons completed and tested an eight-stage axial compressor, known as *Alice,* with an RAE-designed blading similar to that of *Anne* and having a diameter of 9½ in. *Alice* ran more slowly than *Anne,* with a smaller pressure rise but higher efficiency. Detailed studies of the B10, *Anne,* and *Alice,* together with information from the Swiss Brown-Boveri Co., led to a series of schemes in which the air flowed without bends through a single compressor, an annular-combustion chamber, the compressor turbine, and a power turbine.

Construction of a propeller gas turbine on these principles was begun by Metropolitan-Vickers in 1940. Known as the "D11," it was designed to give 2,000 bhp; but the work was interrupted and subsequently abandoned owing to the clear necessity (demonstrated by the Whittle achievements with centrifugal compressors) of first creating an axial-flow jet engine.

Consequently, in July, 1940, Metropolitan-Vickers began design work on an engine of this type, designated "F2," based on preliminary designs

by Constant. It had a nine-stage axial-flow compressor, a single annular-combustion chamber, and a two-stage turbine, all on the same shaft. A pair of these early engines was installed in a specially modified Gloster Meteor (F9/40) twin-jet fighter aircraft; and the first British flight of an axial-compressor type of jet-propulsion gas-turbine aircraft took place Nov. 13, 1943.

The latest version of this engine is the F2/4, which has a 10-stage compressor and a single-stage turbine, producing a thrust of twice the amount of the original engine at the expense of very small increases in weight and over-all dimensions. Its very small diameter enables it to be mounted within a nacelle of only 42 in. over-all diameter. Over-all length is 13 ft 3 in.; net dry weight, 1,700 lb; and static sea-level thrust, 3,500 lb. This unit uses basically the same system as the German BMW-003 but is much more powerful. One model of the F3, a new development featuring a thrust augmenter, was built in 1944, producing 4,000 lb static sea-level thrust (see engineering notes on this unit, page 89). Two of the Metro-Vick F2/4's are scheduled to power the Saunders-Roe S.R.1 flying-boat jet fighter.

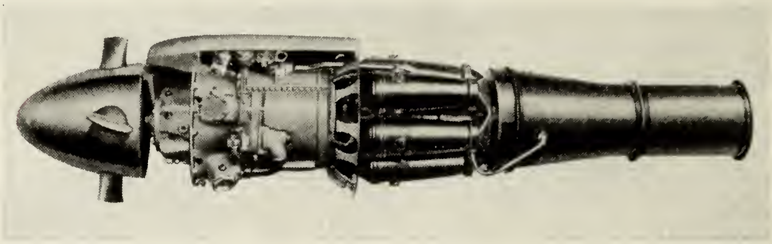
Another of the early axial-compressor units was built by the British General Electric Co. (Fraser & Chalmers Works) and was known as *Ruth*. It had twice the air flow of *Alice* or *Anne* but gave the same pressure ratio as *Anne*, with only six instead of eight stages. An experimental turbocompressor based on Dr. Griffith's scheme of 1929 was also designed at the RAE in 1938, built by Armstrong-Siddeley in 1939, and run in 1940. Had this work been undertaken 10 years earlier, it might well have had a definite influence on the entire aircraft gas-turbine development in England.

To complete this very brief survey of axial-compressor developments before examining the centrifugal type, it should be noted that Armstrong-Siddeley was given its first gas-turbine contract in November, 1942. At that time, there was an overwhelming concentration on the centrifugal-compressor type (except for Metro-Vick); hence Armstrong-Siddeley, to restore the balance partially, began work on the ASX, a 14-stage axial-flow compressor engine with a two-stage turbine and 11 separate combustion chambers.

ASX tests began in April, 1943, the unit developing maximum thrust of 2,600 lb static at sea level. Tests of the compressor have established an adiabatic efficiency of 87 per cent. In this design, intake air enters through a series of ports situated midway along the engine between the rear ends of the combustion chambers, and thus a reverse flow is introduced. Take-off and combat thrust are set at 2,600 lb at 8,000 rpm for a

fuel consumption of 1.03 lb per hr per lb and a weight of 1,900 lb. This engine, adapted to drive a propeller, gives 3,600 shp and 1,150 lb thrust. It is known as the "Python" and first ran in April, 1945. It passed its 25-hr-type test run in the autumn of 1946, and shortly afterward two of the units began a period of flight testing as two of the power plants of the four-engine Lincoln heavy bomber.

The design team at Coventry that was responsible for the Python, most powerful propeller turbine now under flight test, has also produced a small unit called the Armstrong-Siddeley "Mamba." The design called



Armstrong-Siddeley Mamba lightweight propeller/turbine with shaft power of 1,010 hp and a static thrust of 320 lb. Diameter is 27 in.; weight 750 lb. Bench-testing was completed by the end of 1946, and flight tests (four units) in a new version of the Miles Marathon are due in 1947. Due also to power the Vickers Viceroy and Armstrong Whitworth AW 55.

for a sea-level take-off performance of 1,000 shp plus 320 lb S.T. This power is approximately equal to 1,120 hp in a reciprocating engine, but the installed weight of the Mamba is expected to be about 50 per cent that of a corresponding piston-engine installation, while the frontal area represents only 30 per cent of such installation. Dry weight of the Mamba is 750 lb, and diameter is 27 in. Within 6 months of its first test run in early 1946, the full shaft horsepower and thrust were achieved. One of the planned Brabazon types of civil aircraft is the Miles Marathon medium airliner, now powered by four Gypsy Queens. During the latter part of 1946, a fleet of 25 Marathon Mk. V's was ordered, an advanced version to take four Mamba gas-turbine propeller engines, or turboprops. Another is the Armstrong Whitworth 24-seat airliner now being built, to be powered by four Mambas.

As to the development of the centrifugal-compressor gas turbines, it is of special interest to get the early portion of the story in the words of Air Commodore Whittle himself, as given in a lecture before the IME, London. He called attention to the fact that the constant-pressure gas turbine is an old idea and that there had been frequent attempts to pro-

duce a practicable engine of that type, the failures leading to a general belief in the engineering world that it had no future. He sums up this point of view as follows:

The main argument against the gas turbine was that the maximum temperatures permissible with materials available, or likely to be available, was such that the ratio of positive to negative work in the constant-pressure cycle

Photograph by F. Lumbers, Leicester

Air Commodore Frank Whittle, C.B.E., inventor of the Whittle jet engine, patented in January, 1930. He is now technical adviser on engine design and production to the Controller of Air Supplies, British Ministry of Supply. He was awarded the Guggenheim Gold Medal for 1946, for his achievements in aeronautics and also received honors from the Institution of Mechanical Engineers (London) and the Royal Aeronautical Society.

could not be great enough to allow of a reasonable margin of useful work to be obtained, after allowing for the losses in the turbine and compressor. There seemed to be a curious tendency to take it for granted that the low efficiencies of turbines and compressors commonly cited were inevitable. I did not share the prevalent pessimism, because I was convinced that big improvements in these efficiencies were possible, and, in the application of jet propulsion to aircraft, I realized that there were certain favorable factors not present in other applications, namely:

1. The fact that the low temperatures at high altitudes made possible a greater ratio of positive to negative work for a given maximum cycle temperature
2. A certain proportion of the compression could be obtained at high efficiency by the ram effect of forward speed, thereby raising the average efficiency of the whole compression process
3. The expansion taking place in the turbine element of such an engine was only that which was necessary to drive the compressor; and therefore only part of the expansion process was subject to turbine losses.

(NOTE: Air Commodore Whittle included among others who refused to conform to the prevalent pessimistic view regarding gas turbines the small group at the RAE led by Dr. Griffith and Constant and a few engineers of the Brown-Boveri Co. led by Dr. Meyer, its chief engineer.)

In 1928, while still a cadet at the Royal Air Force College at Cranwell, Whittle described in a thesis the possibilities of jet propulsion and of gas turbines. He wrote: "It seems that as the turbine is the most efficient prime mover known, it is possible that it will be developed for aircraft, especially if some means of driving a turbine by petrol could be devised."

Eighteen months later, he conceived the idea of using the gas turbine *for* jet propulsion, and it is this association of the gas turbine and jet propulsion that constitutes the chief novelty of his work. His first patent was dated January, 1930; and although it was presented to the Air Ministry, it was turned down on the ground that the practical difficulties in the way of developing a gas turbine were too great.

However, in May, 1935, while Whittle was at Cambridge as an engineer officer, he was approached by two ex-RAF officers, R. D. Williams and J. C. B. Tinling, who suggested that they should try to get something started. Arrangements were finally completed with a firm of investment bankers, O. T. Falk and Partners; and after a wholly favorable report on the project by M. L. Bramson, a consulting engineer, Power Jets, Ltd., was formed in March, 1936. A proportion of the shares allotted to Whittle was held in trust for the British Air Ministry. In June, 1936, the new company placed an order with the British Thomson-Houston Co. for manufacturing an engine in accordance with Whittle's requirements, except for certain combustion components, instruments, and accessories.

The engine was a simple jet-propulsion gas turbine with a single-stage centrifugal compressor, designed to have a compression ratio of 4:1, driven by a single-stage turbine. There was a single combustion chamber between the compressor and turbine. It was a remarkable venture, even apart from the high compression ($2\frac{1}{2}$:1 had not been exceeded hitherto). The breathing capacity in proportion to size and the combustion intensity were far beyond anything previously attempted. Finally, they sought to get over 3,000 shp out of a single-stage turbine wheel of about $16\frac{1}{2}$ in. outside diameter and to do it with high efficiency.

Whittle was fairly confident regarding the turbine and compressor elements but felt that the combustion system was beyond his depth. He enlisted the aid of A. B. S. Laidlaw of Laidlaw, Drew & Co. While the rest of the engine was being designed and made, combustion experiments were carried out on the British Thomson-Houston premises with apparatus supplied by Laidlaw, Drew & Co. When sufficient data had been collected, Power Jets, Ltd., gave this firm a contract to design and manufacture the combustion chamber.

The tests on the complete engine began on Apr. 12, 1937. The compressor performance was not up to expectation, and the combustion problem was only partly solved. But the Air Ministry was sufficiently impressed to place contracts with the firm for further experiments. British Thomson-Houston undertook the reconstruction of the engine, and further combustion experiments were carried out. After three weeks of intermittent testing during April and May, 1938, a turbine blade failed, showing that combustion was still unsatisfactory. A second reconstruction was undertaken, and the third engine put on the test stand in October, 1938. (This engine continued working until February, 1941, before a turbine failure halted its trail-blazing career.)

In the summer of 1939, after nearly ten months of testing the third model of the experimental engine, the Air Ministry ceased to regard the project as a matter of long-term research and accepted the fact that Whittle and his associates had the basis of a practical airplane engine. As a result, Power Jets received a contract for a flight engine; and a short time later, a contract was placed with the Gloster Aircraft Co. for the manufacture of an experimental single-unit jet fighter to specification E28/39. Thereafter, the Power Jets group, the British Thomson-Houston engineers, and the Gloster designers, chief of whom was W. G. Carter, worked in close collaboration. This first flight engine was known as the "W1" and was actually designed by Whittle.

From unairworthy parts and spares of the W1 engine, a bench unit called the "W1X" was assembled and run by Power Jets during 1940;

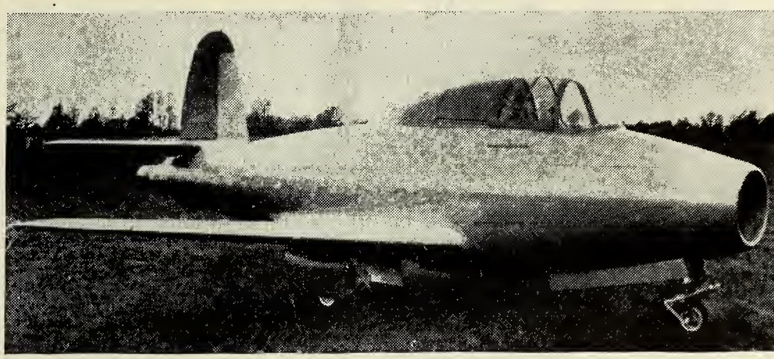
and when the W1 engine was delivered by Thomson-Houston, Power Jets incorporated in it the results of the experience gained with the bench engine. Then, after preliminary bench tests, the W1 was put through a 25-hr bench test to clear it for flight test. The clearance permitted approximately 10 hr flying with the engine.

In the meantime, the E28/39 had been completed by Gloster Aircraft and during April, 1941, was taxied with the W1X engine installed, as

Mr. W. George Carter, chief designer, Gloster Aircraft, Ltd. Designer of the E28/39 and the F9/40 Meteor.

the W1 was still undergoing its final tests. In the course of these taxiing trials at Hucclecote (Gloster's airfield), the aircraft got the bit in its teeth and actually left the ground for a few seconds. Shortly afterward, the flight engine—W1—was installed, and on the evening of May 14, 1941, Flight Lt. Philip E. G. (Jerry) Sayer did the taxiing trials; on May 15 he made the first real flight, being airborne for 17 min and doing speed runs at 2,500 and 4,000 ft. After the first flight test, Sayer turned to a fellow pilot, who was later to fly the Meteor, and remarked with conviction, "Jet propulsion is going to revolutionize everything, old boy. This is only the beginning—trying to make sense of a dream—but the implications are terrific." (Jerry Sayer, pioneer jet-propulsion test pilot, also taxied the F9/40 Meteor in July, 1942, before its full-rated jet engines were installed but died in October as a result of a collision while flying a Typhoon in the clouds.)

The flight program was completed in a fortnight, the seventeenth and last flight of this first series being completed on May 28. The total flying time was 10 hr 28 min and had been completed without incident. The aircraft, which had in most of its 17 flights taken off at 3,691 lb gross weight, with 81 imp gal of paraffin fuel, performed admirably, in some cases exceeding the then top speed of the Spitfire at all heights. The W1 engine which, including its 25-hr bench test and running in the aircraft, had run 39 hr 57 min, was found on dismantling to be in excellent condi-



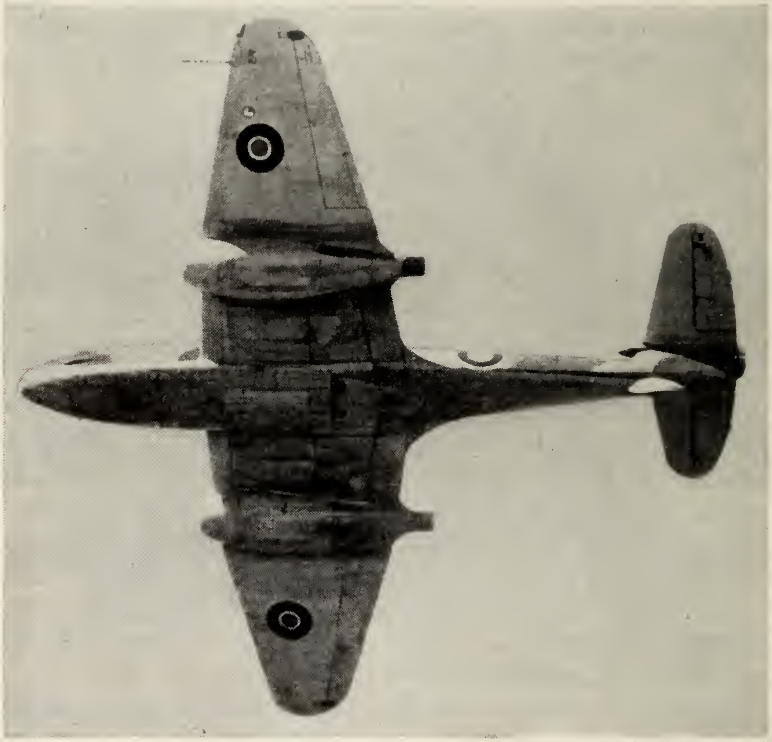
The first British experimental jet fighter, E28/39, which flew on May 15, 1941, with the late Flight Lt. P. E. G. ("Jerry") Sayer at the controls. Power plant was the Whittle W1, designed by Power Jets, Ltd., and built by British Thomson-Houston Company. (*Courtesy of Power Jets, Ltd.*)

tion. This historic unit had a thrust of 855 lb at 17,750 rpm, its maximum speed. Its installed weight was 623 lb.

Although the Germans, as has been seen, actually had a jet-propelled aircraft in the air earlier, the engine used was a type shortly afterward abandoned; and successful flight trials of the Jumo-004, which they ultimately used in quantity, did not take place until some time after the British flight trials. On the other hand, the W1 was the parent of a successful series of British and American engines.

It may therefore be claimed with justice that the Gloster E28/39, popularly known as the "Squirt" but never officially named, was the first *successful* airplane using the gas-turbine jet-propulsion engine. The engineering world is heartily agreed on the validity of this claim and also on the fact that these jet-powered flights opened an era for aviation second only in importance to the original flight of the Wright brothers. Major credit for the successful flight of the E/28, unofficially called the "Pioneer," goes to Frank Whittle, George Carter, and Jerry Sayer.

As the design work on the E28/39 tapered off during 1940, Carter and his colleagues at Gloster began to give their attention to its successor. This was designated the F9/40, later named the "Meteor," and was designed as a fighter for the RAF, with Ministry of Aircraft Production



British Official Photograph

RAF Gloster Meteor I, twin-jet fighter plane, which operated from British bases against the V-1 buzz bombs in the summer of 1944 and from bases on the continent during the last few months of the war.

expectations that it would be completed in time to participate in the war. In a limited way, the expectation was realized.

The engine for this airplane was the W2, designed by Power Jets and built by British Thomson-Houston. The drawings were also turned over to the Rover Co. in April, 1940, based on an Air Ministry decision that henceforth Power Jets would confine itself to research and development and the Rover organization would do the production, a function later taken over by Rolls-Royce.

The first W2 (Rover) engine began running at Power Jets in April, 1941, one year after the project was initiated. Results were somewhat

disappointing, as the engine surged at a speed well below the maximum designed rpm. The Thomson-Houston version, modified by Power Jets and known as the "W2 Mk. IV," was also prone to surging. However, by that time, Power Jets had come up with its design of the W2B, which ranks among the classics of British aircraft gas turbines.

From it stemmed the Welland, power plant of the Meteor I; and the Derwent, power plant of the Meteor III and the record-breaking Meteor IV. Development of both of these was done by Rover and completed by Rolls-Royce. The Rover-Power Jets W2B also was the basis of the General Electric Type I engines, of which the I-A flew in the Bell XP-59A and the I-16 in the P-59A Airacomet and Navy's Ryan FR-1 Fireball, which also has a conventional reciprocating engine.

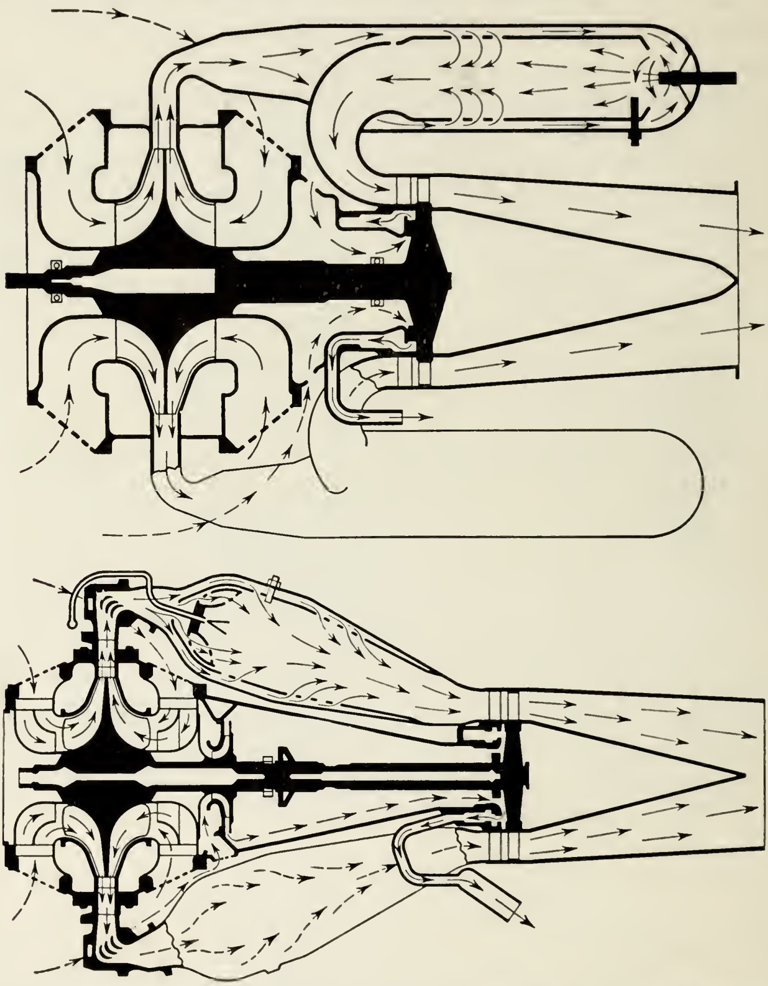
The W2B had a design thrust of 2,000 lb. A brief summary will indicate the Power Jets developments, then the Rover developments. The first modification was the W2/500, which first ran in September, 1942, and which increased the turbine blades from 2.455 to 2.73 in. in length and from 0.8 to 1.2 in. in chord. Performance was 1,755 lb thrust at 16,750 rpm. A change of diffuser design and a further increase in the length of the turbine blades in the W2/700 brought the thrust to 2,040 lb but resulted in a series of impeller failures. This was corrected by using a design developed by General Electric, resulting in a temporary drop of 150 lb in thrust; but with other improvements, this was more than regained to the tune of 2,130-lb thrust.

The final engine in the W2B series developed a thrust of 2,485 lb at 16,750 rpm, with a fuel consumption of 1.05 lb per hr per lb thrust, a yardstick applicable to all types of aircraft gas turbines. Although this engine fitted into the same space as the original W1, its thrust was almost three times as great (2,485 vs. 855), whereas its weight was only 50 per cent greater.

In the autumn of 1941, the Ministry of Aircraft Production adopted a policy of competitive development in the aircraft gas-turbine field and encouraged the Rover Co. to press ahead with some of its distinctive ideas to improve performance and reliability of the W2B engine. The company was able to improve the performance of the engine by introducing the B23 design of blower casing and diffuser system, which appreciably lifted the surging speed. Progress in other directions helped to bring this engine, designated the "W2B 23," to the form later known as the "Welland," which went into the production of Meteors, final stages of development being carried out by Rolls-Royce.

Early in 1940, Power Jets had sketched out a version of the Whittle engine with a so-called "straight-through," or through-flow, combustion

system in place of the reverse, or "return-flow," system. Power Jets did not regard this design with favor at the time, mainly because it involved



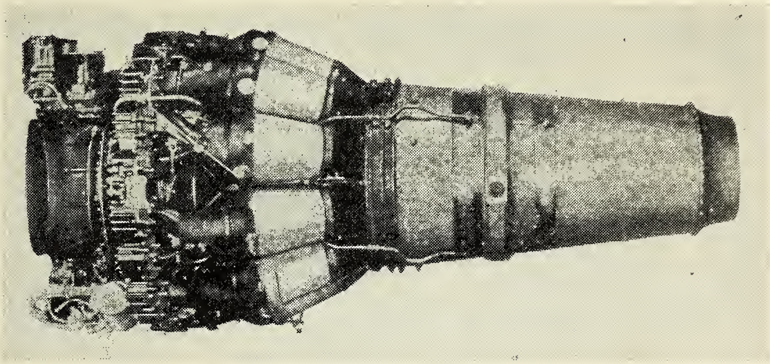
Comparison of "return-flow" (*above*) and "straight-through" (*below*) combustion systems on the Whittle-type of centrifugal-flow double-sided impeller jet engines.

a much longer shaft between the compressor and turbine and required a third bearing.

The Rover Co., however, then much concerned with production problems, believed that the through-flow design would ease the manufacture of the sheet-metal combustion-system components and decided to try it.

The prototype, known as "W2B 26," was designed in March, 1942, and test-run in May, 1942. This, in turn, served as the prototype of the famous Derwent engine, development of which was begun by Rover and completed by Rolls-Royce when that company formally took over the Rover work on gas turbines on Apr. 1, 1943, giving to Rover its work on tank engines. The two firms had for some time been in close association, and the exchange of duties was effected with the minimum of disturbance.

The Rover Co. was thus in the gas-turbine field during its most difficult period, and the step that it took in the change-over to through-flow com-



The de Havilland Ghost II turbojet resembles the Goblin in layout but with differences of detail, including reduction from 16 to 10 combustion chambers. Over-all diameter is 53 in.; static sea-level thrust, 5,000 lb. Power plant of a new de Havilland single-seater, single-jet fighter.

bustion is in consequence the more creditable. Naturally, the change occasioned technical controversy; but there is now little doubt that under current conditions the through-flow arrangement, originally demonstrated on the Halford H1, has the advantage over the reverse-flow system of the classic Whittle engine.

Before the Halford-de Havilland developments are sketched, the comparative advantages and disadvantages of reverse vs. through-flow may be briefly summarized as follows:

The big advantages of through-flow are

1. Greater cross-sectional area for combustion within a given over-all diameter
2. Involves no sharp bends and so has lower pressure loss
3. More even air distribution
4. Simpler to manufacture
5. Easier to maintain

Its main disadvantage (less so as superior metals are being developed) is that it subjects turbine stator and rotor blades to direct high-temperature radiation from the flame, with possibly higher metal temperatures.

In January, 1941, at the suggestion of Sir Henry Tizard, who was then with the Ministry of Aircraft Production, Maj. Frank B. Halford, with a series of notable piston engines to his credit (including the Gypsy series, Napier Dagger, and 24-cylinder Sabre), was brought into the gas-turbine field. Halford's organization worked on this problem (as on others) in close association with the de Havilland Aircraft Co., Ltd., becoming, in

Photograph by Charles E. Brown

The de Havilland Vampire, test-flown in September, 1943, a product of coordinated design of aircraft and engine divisions. Top speed is over 550 mph. First all-jet aircraft to take off and land on a carrier.

March, 1944, without change of personnel, the de Havilland Engine Co., Ltd., with Major Halford as chairman and technical director.

On the basis of his long experience with centrifugal blowers and with close knowledge of Whittle's progress with his engine, Halford decided to use a single-sided impeller instead of Whittle's double-sided impeller and a through-flow combustion system in contrast to the reverse-flow system favored by Whittle. The whole conception of the Halford H1 turbojet, later to be known as the "Goblin," power plant of the de Havilland Vampire, had what the company calls an "elegant simplicity." De Havilland thus became builder of both the air frame and the power plant, and success of the Vampire is attributed to this fact. A second de Havilland turbojet, called the "Ghost," was a later development.

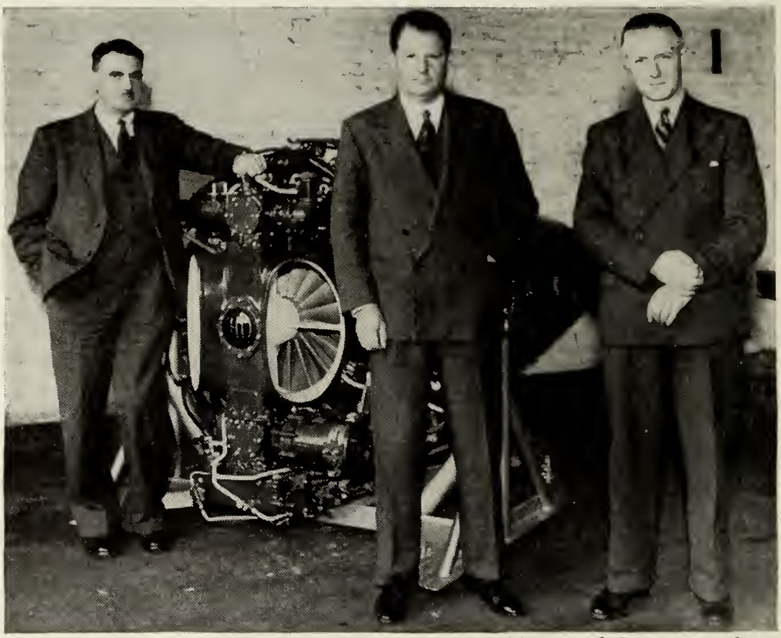
Design work was started in April, 1941; and testing of the first Halford H1 began in April, 1942, following the general pattern of about one year for these engines, after the pioneering W1. About a year later (March, 1943), a pair of Halford H1's flew in a modified Meteor, with a rating of 2,000 lb maximum static sea-level thrust. The H1 Goblin flew in the Vampire in September, 1943, and in the prototype Lockheed XP-80

in January, 1944. The Goblin II, powering the Vampire and de Havilland 108 Swallow, is rated at 3,000 lb, and a considerable amount of bench and flight testing of advanced models has been done at 3,400 to 3,500-lb thrust.

The de Havilland 108 Swallow, built to explore swept-back wing design as a prelude to large, high-speed transport craft. These advanced-type wings were fitted to a standard de Havilland Vampire fuselage, powered by the de Havilland Goblin I jet engine.

Rolls-Royce interest in gas turbines dates at least from the time when Dr. Griffith left the RAE in the summer of 1939 to join the company; it may even have been somewhat earlier than this, as the company had carried out a number of experiments on the promising contraflow-contra-rotating class of engine first proposed by Dr. Griffith in 1929. In addition, the company had for many years been interested in the development of centrifugal blowers for reciprocating engines; and during production

of the first Whittle engines, the technical experience of the company's Derby engineering group and the facilities were made available for fabricating components such as casings, turbine blades, and oil pumps. When the first flight of the Gloster E28/39 took place in May, 1941, Rolls-Royce interest was further stimulated; and in June, the company



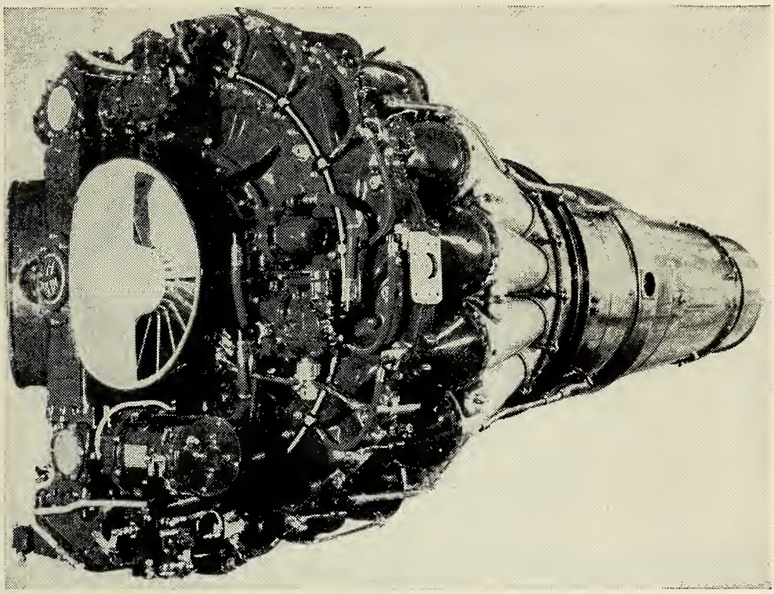
Photograph by Lamson Clark

The de Havilland "Goblin" turbojet, with the de Havilland engine-development team. *Center*, Maj. Frank B. Halford, chairman and technical director of the de Havilland Engine Co., Ltd.; *left*, Mr. John L. P. Brodie, director of the company, in charge of the engineering division; *right*, Mr. E. S. Moult, chief engineer.

set up a test plant at Derby for development work on centrifugal compressors. Early in 1942, an order was received for an engine known as the "WR1," based on the Whittle-Power Jets W2B and incorporating a number of Rolls-Royce ideas on blower, turbine, and mechanical design. Dr. Stanley G. Hooker, chief engineer, headed up the entire aircraft gas-turbine program, and J. P. Herriot was development engineer. Within three years, Rolls-Royce had achieved an outstanding position in the field.

With the experience thus gained, Rolls-Royce assumed responsibility for Meteor power-plant development and production, taking over from Rover (as we have seen) on Apr. 1, 1943. In that month, the first Rolls-

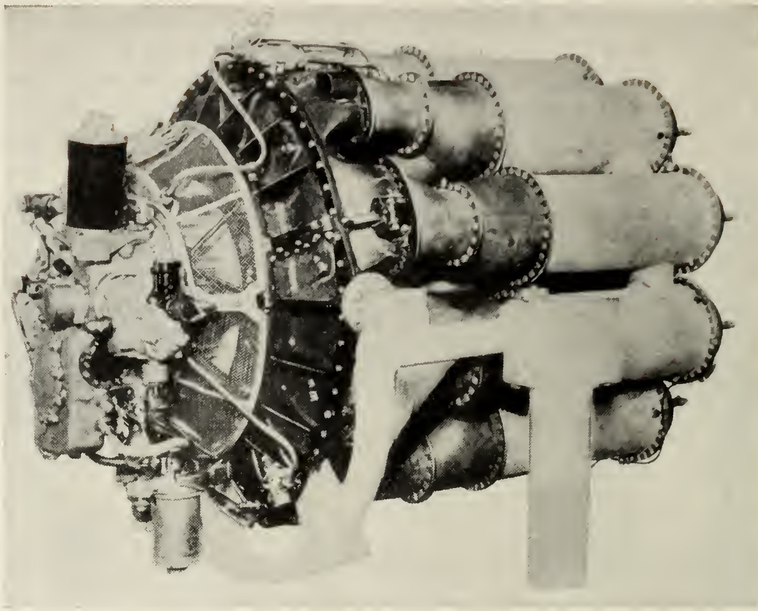
Royce version of the Whittle engine passed a 100-hr type test. Giving 1,700-lb thrust, it was 43 in. in diameter and weighed 850 lb. Named the "Welland," it became first of the Rolls-Royce "river" class of jet-propulsion gas turbines (named for several of England's rivers). Deliveries began in May, 1944, when the Welland had passed a 500-hr type test,



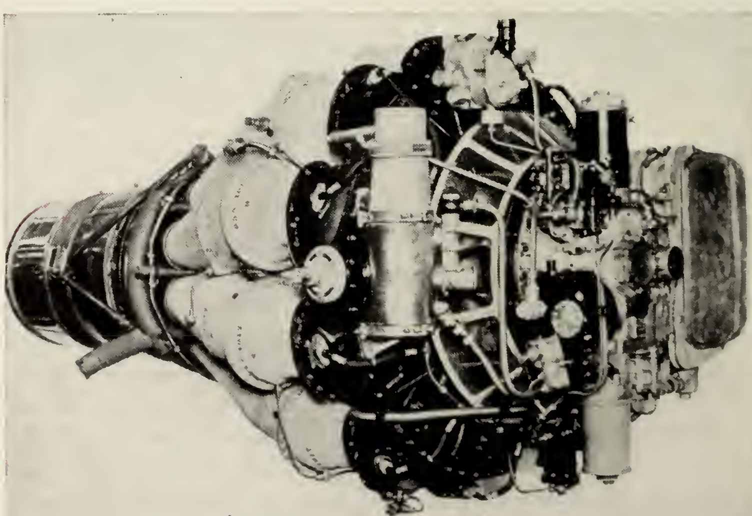
Close-up of the de Havilland Goblin II turbine/jet engine, power plant of the de Havilland Vampire, Sea Vampire, and the de Havilland 108 Swallow, features a single-sided impeller and was the first turbojet to adopt the straight-through combustion system. Rated for production at 3,000 lb of thrust.

and went into active service in the Gloster Meteor with a life of 180 hr—between overhauls.

Meanwhile, work was proceeding on a development of the Rover W2B/26 through-flow, designated the "W2B/37," or "B/37" for short. This engine was subsequently named the "Derwent," second of the river series, and was similar in layout to the B/26 but incorporated a larger turbine and other modifications. Drawings and construction were completed in the remarkably short time of 105 days (April to July). The first test was run in July, 1943; a 100-hr type test at 2,000 lb thrust was made in November, 1943; and in April, 1944, the first flight test was completed. Installed as a replacement for the Welland in the Gloster Meteor, it increased the thrust from 1,700 to 2,000 lb per unit, with the same over-all nacelle diameter and weight increase of only 70 lb.



The W2B engine, designed by Power Jets, developed by Rover, and finally developed by Rolls-Royce as the "Welland," first of the "river" series, and original power plant of the Meteor.

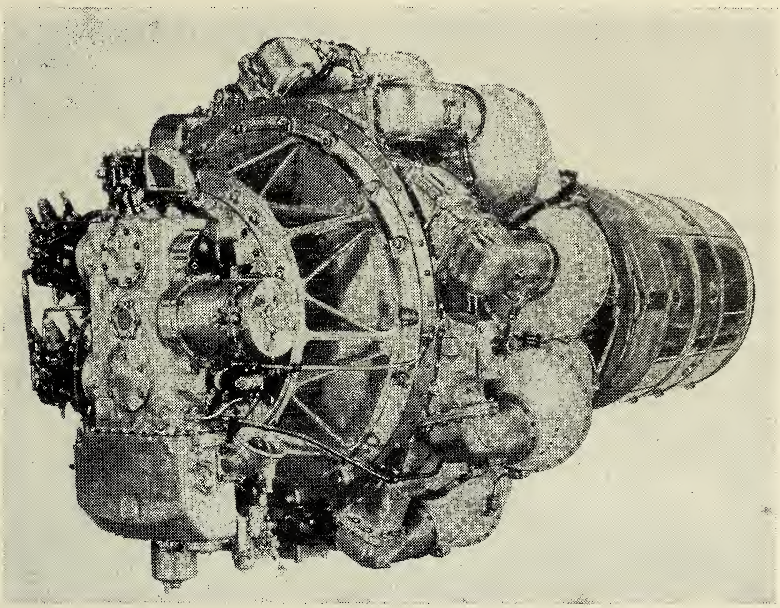


British Official Photograph

Rolls-Royce Derwent V turbine/jet engine, power plant of the Meteor IV, featuring a straight-through combustion system, with an output of 4,000 lb of static thrust.

The satisfactory performance of this new aircraft gas turbine gave great promise for further development, and a continuous program involving many 100-hr tests was carried out, culminating in a successful 500-hr type test without strip or major replacement of any kind.

Latest of the series is the Derwent V—embodying the form of diffuser found so successful in the W2/700 and including some features of the



Rolls-Royce Nene jet-propulsion engine, which has a maximum thrust rating of 5,000 lb (with water injection, 6,000 lb) with a weight of 1,650 lb. Has been test-flown in the P-80, the Supermarine E 10/44, and other British jet aircraft.

later Nene—now in active service as the power plant of the Meteor IV. It was one of these Mark IV Meteors ("Britannia"), flown by Group Captain Wilson, that early in November, 1945, established a world speed record by streaking over a measured course at 606 mph average for three runs. Official rating of the Derwent V is 3,500-lb thrust at 14,600 rpm; but bench and flight tests have been carried out beyond that figure, reported to approach double the original 2,000 lb of the Derwent I. Naturally, the weight has had to go up to some extent, but the thrust-to-weight ratio has been radically improved from 1.86 for the Welland, to 2.08 for the Derwent I and 2.78 for the Derwent V.

During the first 6 months of 1946, by the use of an improved Mond Nickel Company metal in the turbine rotor blades, permitting 15,200

rpm, the available thrust of a few Derwent V turbojets was raised to 4,200 lb (1,905 kg). (Jet-pipe temperatures lay between 720 and 740°C, *i.e.*, 1185 to 1215°F, a 40 per cent increase over those of 1941.) These special engines were installed in two standard service Meteor IV's (EE 549 and EE 550), with certain minor modifications. These were later called "Star Meteors," and the modifications included no radio mast or

Air Commodore Frank Whittle with Dr. Stanley G. Hooker (*right*), chief engineer, Rolls-Royce, Ltd., and J. P. Herriot (*left*), chief development engineer, who saw the Nene I turbojet engine through its 150-hr test at the Naval Air Material Center, Philadelphia, Pa. (*Courtesy of Rolls-Royce, Ltd.*)

armament; the rudder tab was locked; dive brakes were screwed up; tail-plane incidence was adjusted; extra fuel was in three tanks for the increased consumption of the special Derwents; and there was a special cockpit hood reinforced with metal to save the plastic melting from the increased heat. Under the jurisdiction of Air Marshal Sir James Robb, commander in chief of the RAF Fighter Command, a high-speed flight was organized for a fresh attempt on the world speed record of 606 mph. This was headed by Group Capt. E. M. (Teddy) Donaldson and included an additional pilot, Squadron Leader William (Bill) Waterton, and Squadron Leader A. N. Porter, chief technical officer. As weather was of paramount importance, top meteorological specialists were assigned to

the flight. Through July and August, preparations at Tangmere Aerodrome (near Littlehampton, on the coast) for the intricate time measurements, etc., practice flights were made; and on Sept. 7, Group Captain Donaldson achieved an average speed of 991 km (616 mph) for four

Photograph by Charles E. Brown

"Star Meteor" streaking by the eastern end of World Record Course at Rustington in a low-level practice run. Course Controller's hut (checkered) below house, Camera hut at right. (*Courtesy of Aeronautics, London.*)

alternate 3-km runs, according to the standards of the Federation Aeronautique Internationale (FAI).

This represented a Mach number of slightly over 0.81. Squadron Leader Waterton in EE 550 averaged 988 km (614 mph) in his attempt. This was a most remarkable achievement, especially in the light of the fact that the Meteor was first test-flown in April, 1944, with a Derwent I engine of 2,000 lb S.T. at a speed of around 450 mph. This meant an

increase of 37 per cent for the airplane and 110 per cent (4,200 lb) for the engine in less than 30 months. Highest credit should be given to the teams of George Carter of Gloster and Stanley Hooker of Rolls-Royce.

In conjunction with the work on engines for the Meteor, Rolls-Royce began development in February, 1944, of the W2B/41 (or B/41), a bigger and more powerful engine, known as the "Nene." This design appeared so attractive that some of its features were incorporated in the Derwent V. The Nene was designed, built, and run in approximately four months. Present thrust-to-weight ratio is 3.1, with a static thrust of 5,000

Photograph by Charles E. Brown

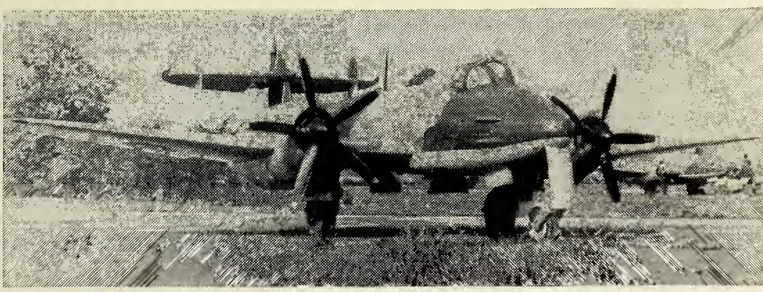
Supermarine E 10/44 Attacker, a 600-mph fighter designed around the Rolls-Royce Nene I turbojet. Pilot's cockpit is pressurized for high-altitude work, and the new ejector seat is standard equipment on the plane.

lb at maximum rpm of 12,400 and a net dry weight of 1,550 lb. Diameter is 49½ in., length is 8 ft 1 in. Fuel consumption is 1.06 lb per lb thrust per hour. (Further details of this outstanding turbojet engine will be found on page 83.)

The Nene I was flown in the P-80 during the summer of 1945 and, at the end of 1946, was the most powerful aircraft gas-turbine engine in production. The Nene I is the power plant of the Nene Vampire, going into service during 1947; the Gloster Ace, successor to the record-holding Star Meteor; a new Hawker design; and the Vickers-Armstrong Supermarine E 10/44 Attacker. Most of these models, plus a new Ghost-powered de Havilland design, are likely to figure in further attempts to achieve higher world speed records. Two Nene I's also power the Armstrong-Whitworth A.W.52 "arrowhead" tailless aircraft, small experimental model of the huge A.W. flying-wing airliner of the not too distant future.

In the export field, although a number of de Havilland Goblin-powered Vampires have been purchased by Sweden and Switzerland, the Rolls-Royce Nene I is holding the spotlight for 1947. Russia was sent a number of them in the autumn of 1946; and Canada has received a few for

the Royal Canadian Air Force, for cold-weather testing in Winnipeg, and for jet aircraft being developed by A. V. Roe & Co., Canada, Ltd.; Roe is also developing its own gas turbine as a long-range project. Australia is planning to build the Nene to power both British aircraft and her own developments. France is to use a Nene in one of the versions of the S.O. 6,000 high-speed research aircraft. (A Jumo-004, a Derwent V, and the Rateau-GT S 65 will power three prototypes.) In the Netherlands, the N. V. Fokker Company is building a medium-sized, 17-passenger, 500-mph airliner to be powered by two Nenes. Interest in South



Modified Gloster Meteor powered with two Rolls-Royce "Trent" gas-turbine engines with airscrew (turboprop). It was the first aircraft to fly with this type of power plant (September, 1945). (*Courtesy of Rolls-Royce, Ltd.*)

America and in China has also been indicated. In the United States, plans are in an advanced stage for Pratt & Whitney to produce (for Navy) an American version of the Nene (see page 159 for details).

Although Rolls-Royce engineers definitely favor the turbojet and not the turboprop, for civil as well as military applications, they have not altogether neglected the propeller. In May, 1944, Rolls-Royce began to convert a few Derwent units to drive five-bladed propellers through reduction gearing. In this form, the power plant is called the "Trent." Two of these units were installed in a modified Meteor for flight-test work, beginning in September, 1945; and thus the Trent became the first turbine propeller to fly. This was, however, a purely experimental project, not to say a makeshift. Their first serious turboprop designed from the ground up is the Clyde, with a nine-stage axial-flow compressor, a low-pressure turbine, a centrifugal compressor, and a high-pressure turbine. This seemingly complicated arrangement had the advantages of permitting great flexibility of operation and of starting by an unprecedentedly light (10 lb) starting motor. Designed for 3,000 shp and 600-lb jet thrust, the Clyde has been running on the bench since early 1945, with flight tests due in the autumn of 1947. Rolls-Royce also has a small, light-

weight propeller turbine known as the "Dart" (1,000 shp, 350-lb exhaust thrust), with two-stage centrifugal compressor and single-stage turbine, which has been undergoing bench tests since August, 1946. This project is now being flight-tested.

The development by Rolls-Royce of the Clyde, with its axial-flow compressor, indicates a broadening of interest from the highly concentrated war development of the Whittle type of turbojet engine in two directions. One is the practicability of the turbine-propeller engine to fill at least an interim need in the 350- to 450-mph speed bracket with aircraft of substantially the early postwar configuration. The other is that given the added time for development, the axial-flow type, with its smaller frontal area, greater pressure ratio and greater over-all efficiency, has an important place in the rapidly advancing jet field. At the time of the world speed-record attempts in the late summer of 1946, rumors were current that one of the Star Meteors would be powered by Rolls-Royce axial-flow turbojets in the 6,000-lb-thrust class. It may be that such a unit will be announced during 1947.

Without detracting from the valuable pioneering and developmental work of the other companies in connection with both axial-flow and centrifugal types of aircraft gas turbine, it does not appear out of place to record a statement made by Air Commodore Whittle in connection with Rolls-Royce as the company that finally developed and actually produced considerable numbers of gas turbines for operational and combat use in World War II. He said

> It has always seemed to me that the part played by Rolls-Royce in the Battle of Britain has never received the prominence it deserved. Every Hurricane and every Spitfire that took part in that battle was powered with a Rolls-Royce engine. One day in 1942, their Mr. Hives told me with considerable emphasis that Rolls-Royce had decided to go all out for the gas turbine; that was a dramatic moment for me . . . and a major landmark in the history of gas-turbine development.
>
> It is a source of great satisfaction to me personally, and to the engineers at Power Jets, Ltd., that Rolls-Royce have directed their main effort in gas turbines along the lines laid down by Power Jets, and I am happy to say that throughout the development, Rolls-Royce engineers have never failed to give due weight to the advice and opinions of myself and the rest of Power Jets team. We in turn have learned much from their work.

Finally, mention should be made of an aircraft gas turbine designed by the Bristol Aeroplane Company especially for long-range medium-speed aircraft, and known as the "Theseus," following the names of Greek mythological characters established in the line of air-cooled radial-piston engines—Jupiter, Hercules, and Centaurus.

In the Theseus, a conventional propeller is driven by an independent turbine, and a heat exchanger for heat regeneration from the exhaust gases is utilized. These features provide good propulsive efficiency over a wide range of aircraft speeds and a fuel consumption competitive with that of piston engines of comparable powers. Some 80 per cent of the power of the engine goes to the propeller, and 20 per cent is used for jet reaction. The unit consists of an axial-cum-circumferential compressor delivering air through the heat exchanger to eight combustion chambers and thence to the three turbine stages, the first two of which drive the compressor and auxiliaries, and the third the propeller, through an epicyclic reduction gear. The gases then pass through the hot side of the heat exchanger to the exhaust jet. In February, 1947, the Theseus began its test flights as two of the four power plants of a modified Lincoln heavy bomber.

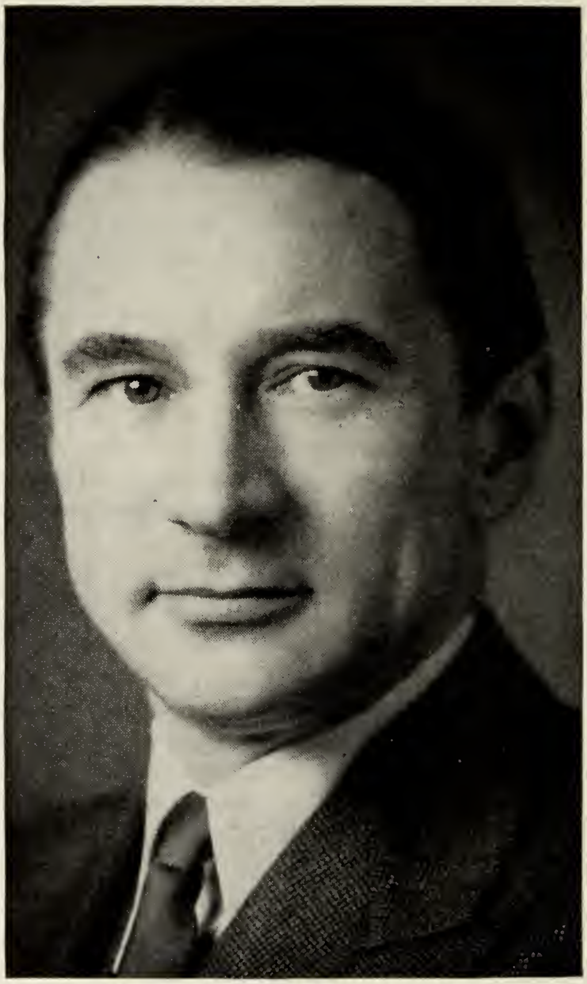
During 1946, Sir Roy Fedden, former chief engineering designer and past president of the RAS, formed the firm of Roy Fedden, Ltd., and is developing a small, light, axial-flow turboprop in the same class as the Armstrong-Siddeley Mamba and the Rolls-Royce Dart. Its 19-in. diameter makes it the smallest of all to date, designed to produce 1,305 shp and 120-lb exhaust jet thrust; its weight is 750 lb.

During World War II, eight major companies were engaged in the development of aircraft gas turbines in Great Britain, not including those working on certain component parts. For the most part, they were manufacturers of engines rather than turbines; whereas in the United States, as will be seen in the following chapters, initial developments in this field were carried out by companies whose experience had been in the steam- and gas-turbine fields, with engine companies coming into the picture at a later stage, either for production or for advanced experimental designs.

To channel effectively the British collective effort; ensure economy in the attempt to produce power units; avoid unnecessary duplication of effort; and pool ideas, testing facilities, and experience, Dr. Harold Roxbee-Cox, chairman and managing director of Power Jets, proposed a Gas Turbine Collaboration Committee. It was formed in October, 1941, under the chairmanship of Dr. Cox and later under Group Capt. G. E. Watt. In October, 1946, Dr. Cox resumed his activities as chairman of the GTCC, now reorganized on a peacetime basis.

Meeting on an average of five times a year, the committee provided the means for the various firms and establishments working on the gas-turbine project to interchange ideas freely and give each other assistance when needed. Subcommittees of experts on various subjects were set up

to deal with specific problems. Three of the meetings were held in the Ministry of Aircraft Production conference rooms (Birmingham or Lon-



Dr. Harold Roxbee-Cox, formerly of Power Jets, Ltd. (Research), and through the war period chairman of the Gas Turbine Collaboration Committee. He is now director of the National Gas Turbine Establishment which took over the research and development of power jets.

don), and all the others took place at the plants of the companies concerned, so that the committee could see the work in progress and the various gas-turbine engines in operation.

The complete frankness that characterized the working of the commit-

tee was a considerable stimulus to individual efforts, and the innovation of wholehearted collaboration proved a great success—so much so, in

The Aeroplane, Copyright

Sir Roy Fedden was for many years chief engine designer for the Bristol Aeroplane Company's long line of poppet- and sleeve-valve engines. He has been president of the Royal Aeronautical Society and led one of the technical intelligence teams into Germany in the late spring of 1945 to investigate research and development progress there. He recently formed his own company and announced the design of a lightweight turboprop.

fact, that the committee—at least up to the time that all jet work was nationalized by the Labor government—was making a strong bid for vigorous survival in the less dangerous but nonetheless difficult atmosphere of peace.

Engineering Notes on the Rolls-Royce Derwent Series

Direct descendants of the original Whittle jet engine, the Derwent-series engines resulted from the work of both the Rover Co. and Rolls-Royce. While Rover engineers were working on the Welland, first of the river class of engines, they developed designs for a through-flow unit, a design that did not find favor with Power Jets engineers because it required a longer shaft and installation of a third bearing.

When Rolls-Royce took over the Rover work, they continued with the design, first of the Derwents, which developed 2,000-lb thrust at 16,500 rpm and had a dry weight of 850 lb.

This engine, the Derwent I, utilizes a two-sided centrifugal impeller, 10 combustion chambers, and a single-stage turbine. Cooling air is brought in from the front housing through short pipes to a small impeller type of fan on the shaft just ahead of the center bearing and directed through a manifold to the center and rear bearings and turbine-disk front face.

A triple-gear type of pump forces lubricating oil to the bearings, with two scavenge pumps returning it through a thermostatically controlled cooler to the oil tank.

Fuel flow is controlled by the pilot's throttle valve, with a barometric control automatically reducing flow with increasing altitude. In starting, the fuel is ignited by two ignition plugs, with balance pipes between combustion chambers to equalize pressure and to provide ignition for all chambers.

Derwent Mks. II and IV each represented a 10 per cent increase in thrust over the I, whereas the Mk. III was an experimental unit built for boundary-layer-control studies.

The Derwent V is an 85 per cent scaled-down version of the Nene. Compared with the Derwent I, its compressor has an increased capacity, and the unit has 9 in place of 10 combustion chambers. And fuel control differs, also. On the I, pump capacity was fixed and flow to combustion chambers was controlled by by-passing excess fuel; on the V, pump capacity is varied by an aneroid to reduce supply at altitude.

Derwent I *and Derwent* V *Specifications and Data*

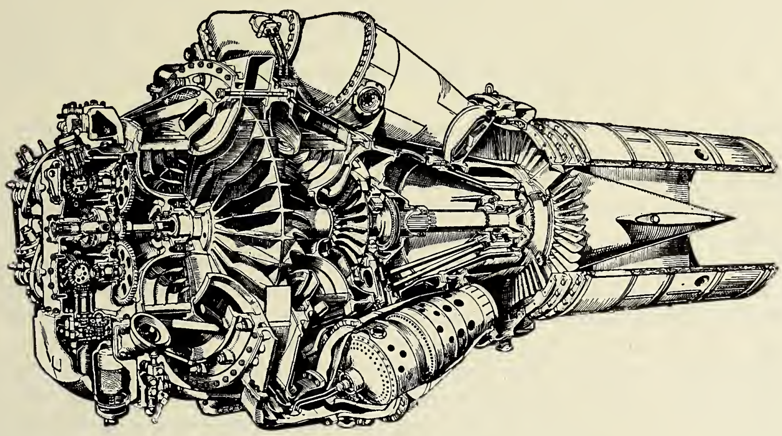
	Derwent I	*Derwent* V
Thrust, static sea level	2,000 lb	3,500 lb
Maximum rpm	16,500	16,500
Thrust, cruising (15,000 rpm)	1,550 lb	3,500
Weight	850 lb	1,250
Length	101.5 in.	83.1 in.
Maximum diameter	42.5 in.	42 in.
Compression ratio	3.9:1	
Impeller diameter	20.68 in.	
Throat area	38 sq in.	
Turbine diameter	17.38 in.	
Maximum jet-pipe temperature	690°C	
Combustion chambers	10	9

An additional change has been made in the discharge-nozzle box; on the V, it is a casting rather than a fabricated unit to eliminate splitting and cracking of welding due to high temperatures. Securing nozzle vanes inside the nozzle box has been improved on the later model by using a buttress type of connection, which reduces differential expansion of vanes and casings.

Another important difference in the two models is in the bearings—the V using roller instead of plain.

Engineering Notes on the Rolls-Royce Nene I

The newest British river class of turbojet developed from the original Whittle designs; the Rolls-Royce Nene I was, in mid-1946, also Great Britain's most



Cutaway of the Rolls-Royce Nene I, most powerful turbojet now in production, with static sea-level thrust of 5,125 lb and 5,400 lb on the bench. Note double-sided impeller, following Whittle design; cooling fan and single-stage turbine all on one shaft. Power plant of more than a dozen fighters and projected transports. To be made at Pratt & Whitney under license. (*Courtesy of Rolls-Royce, Ltd.*)

powerful production unit, having a static sea-level thrust of 5,000 lb at 12,300 rpm at a weight of 1,650 lb and over-all diameter of 49.5 in.

Using a two-sided centrifugal compressor, nine through-flow combustion chambers, and a single-stage turbine, the Nene, or RB-41, was designed early in 1944 to Ministry of Aircraft specifications calling for an engine to develop a minimum of 4,000 lb thrust, with weight not to exceed 2,200 lb and maximum over-all diameter of not more than 55 in. The foregoing figures indicate that these specifications were handsomely beaten. By spring of 1947, the Nene I was turning up better than 5,850 lb S.T. on the bench.

Outward appearance of the Nene is quite similar to the General Electric I-40 (see page 111), power plant of the Lockheed P-80A Shooting Star, which has also been flown with a Nene, achieving a speed of 580 mph.

Designing the engine around a double-sided impeller rather than the single-sided unit employed by the Halford-de Havilland Goblin was dictated, Rolls-

Royce engineers report, by the belief that a greater quantity of air can be consumed for a given frontal area. Use of the double-sided impeller, they maintain, means that it can be 40 per cent smaller in engine diameter for the same air consumption and thrust. Although use of the two-sided impeller requires more clearance of the nacelle, Nene installations are said to require no more than 2 in. increase in over-all diameter.

This unit is comprised of a small atomizer embodied in one unit with an igniter plug. The atomizer is fed fuel from the low-pressure side of the fuel system and is controlled by a solenoid-operated valve which gets current from the low-tension side of the ignition system. In starting, the colenoid is energized simultaneously with the igniter plug, permitting fuel to pass to the atomizer and to be discharged as an easily fired spray. The high-tension spark from the igniter plug ignites the spray, the flame of which in turn lights the fuel spray from the pilot atomizer. An automatic time control cuts out the ignition system, and the solenoid valve is closed by a light spring that cuts off the fuel supply to the igniter plug. Interconnecting pipes carry the flame to the other chambers.

Exhaust assembly consists of nozzle, cone, and jet pipe, mainly double skinned, with the space between skins filled with heat-insulating material. Inside the nozzle is a conical fairing—the base of which masks the turbine disk—which is supported by four long, transverse bolts inside streamlined fairings.

As is the case with the I-40, the accessory case is attached to the front of the unit just ahead of the air intake. Driven at 0.41 engine speed, it contains drives for aircraft accessory gearbox, tachometer generator (top), two fuel pumps (right side), and starter motor (left side).

Lubrication system on the Nene marks a departure from previous Rolls-Royce practice, since a wet-sump setup is used. Bulk of the lube oil is contained in a sump formed by the lower part of the accessory geardrive case. This sump houses pressure and scavenge-oil pumps, two gauze scavenge-oil filters, Purolator high-pressure filter; pressure-relief valve; and deaerater.

Pressure pumps take the oil from the sump through the strainer and into the high-pressure filter, whence it goes to the gearbox to lubricate bearings on the rotor shaft. Scavenge oil from the gearbox and front bearing drains directly into the sump; that from the rear bearing goes to the center bearing housing, then from both bearings to the scavenge pump via the sump base and gauze filters. Oil jets are used at "critical" points to operate in connection with restrictors to supply a controlled quantity of oil to the bearings, holding consumption to less than 1 pt per hour.

In the twin-pump fuel system, the aviation kerosene (plus 1 per cent oil) is fed through a low-pressure valve to a filter mounted beneath the accessory gearbox. From here it goes to the pumps, the lower one of which is set 150 rpm faster than the top governor setting. The pumps are of the oscillating, multiplunger type and have the piston stroke controlled by a swash plate, the angle of which is determined by a spring-loaded servo piston. Each pump has an overspeed governor, which acts on the servo unit to limit pump delivery and keep rpm within safe limits; but in the two-pump system, only the lower governor is used. Incorporated in the system is a barometric pressure control to vary pump delivery according to altitude.

At lower speeds, fuel goes directly from the throttle valve—which takes the combined pump delivery—to the pilot atomizers; but with increasing pump pressure due to higher speeds, the pressurizing valve opens, and fuel goes to main fuel nozzles. Since the throttle is set to permit passage of fuel for idling when it is in closed position, the high-pressure cock is used to stop the engine. Closing this cock completely shuts off the supply to the burners, and a drain passage is opened to allow the burner manifolds to drain back to the pump inlet. There is, in addition, a separate hole drilled in the high-pressure cock for fuel to pass from the pressure line back to the high-pressure fuel-pump inlet to establish an idling circuit during engine shutdown and thus prevent undue pressure build-up in the fuel line.

To facilitate installation in different aircraft, six engine-mount attachment faces, with a range of standardized brackets, are provided. Three alternative drive positions for aircraft accessory drives are provided on the gearbox—upper and lower horizontal and upward inclined drive.

Following are specifications and data of the Nene.

Nene Specifications and Data

Thrust, static sea level,		12,300 rpm	5,000 lb
	200 mph	12,300 rpm	4,620 lb
	400 mph	12,300 rpm	4,390 lb
	600 mph	12,300 rpm	4,450 lb
Cruise	100 mph	11,500 rpm	3,620 lb
	300 mph	11,500 rpm	3,220 lb
	500 mph	11,500 rpm	3,070 lb
Temperature, combustion-chamber inlet (*increase*)			200°C
Temperature, combustion chamber (*increase*)			1150°abs.
Temperature drop, turbine			175°C
Temperature, jet pipe			702°C

Dimensions

Length, over-all to exhaust cone flange	96.8 in.
Length, exhaust cone removed	63.9 in.
Maximum diameter	49.5 in.
Weight (*including accessories but without aircraft accessories or jet pipe*)	1,550-1,600 lb

Engineering Notes on the Halford-de Havilland Goblin II

As noted earlier in this chapter, the main difference between the Halford and *other British* centrifugal turbojets is the fact that Halford units employ the single-sided impeller.

Throughout the development program, the Halford interests have felt that the single-sided impeller had several distinct advantages. The direct ducting of intake air, for example, means that airflow can be increased with relation to the plenum-chamber arrangement. It gives high-velocity entry without flow breakaway, reduces pressure losses, takes fuller advantage of ram effect, and simplifies installation. Although the two-sided impeller has a greater

capacity for a corresponding engine diameter, the need for getting air to the rear face means a larger over-all installation diameter.

The Goblin II's 31-in. diameter impeller has 17 vanes and delivers air to the combustion chambers at a 3.3:1 pressure ratio at a maximum speed of 10,200 rpm, giving vane-tip speed of 1,430 fps. One of the principal differences between the Goblin I and II is in the design of the labyrinth seal on the aft face of the impeller, which matches with grooves on the sealing plate. In the later engines, a semibuttress shape is used in place of the full buttress. Clearance of the lips on a cold engine is 0.015 in., with expansion under heat bringing an overlap of 0.075 to 0.095 in.

Goblin II's hollow rotor shaft, machined from a steel forging, is bolted to both impeller and turbine disk. The rotor assembly is supported on front and rear roller bearings, the former being mounted ahead of the impeller on a stub shaft and cooled by intake air, whereas the latter is mounted just ahead of the turbine disk and cooled by ducted air bled from the compressor between combustion chambers. No thrust bearing is required, since the single-sided impeller tends to pull forward, counteracting the pull aft of the turbine.

This single-stage turbine has 83 blades made of Nimonic-80 alloy. Blade roots are the serrated Christmas-tree type, fitting into serrations on the turbine disk and held in place by peening the roots on both sides, the upstream peening being heavier to resist rearward thrust.

The 16 flowerpot-type of combustion chamber consists of three main elements: outer casing, flame tube, and burner. The tapered cylindrical outer casing is deep-drawn mild steel, protected inside and out by nickel plating, fastened by a flanged joint to a die-cast aluminum expansion chamber (at the upstream end), which is bolted to the diffuser casing. The downstream end is attached to the turbine-nozzle junction box by a piston ring-tube expansion joint.

The flame tube is concentric with the outer casing and held in place by three pins attached to the outer casing but permitted to slide inside the sockets for radial expansion. The burner comprises outer and inner cup-shaped caps and flared cover plate. Some 20 per cent of the air entering from the compressor goes through a metering annulus into the inner cap for primary combustion, some of it going through a swirler around the fuel nozzles, and the remainder around the swirler to give turbulence to mix fuel and air. The remaining 80 per cent of the air, as it passes through an an-

Specifications and Data

Thrust, static sea level	3,000 lb
Maximum rpm	10,200
Weight	1,550 lb
Length	
Maximum diameter	
Compression ratio	3.3:1
Impeller diameter	31 in.
Turbine diameter	
Maximum jet-pipe temperature	
Combustion chambers	16

nular space between outer casing and flame tube, is brought into the latter through ports.

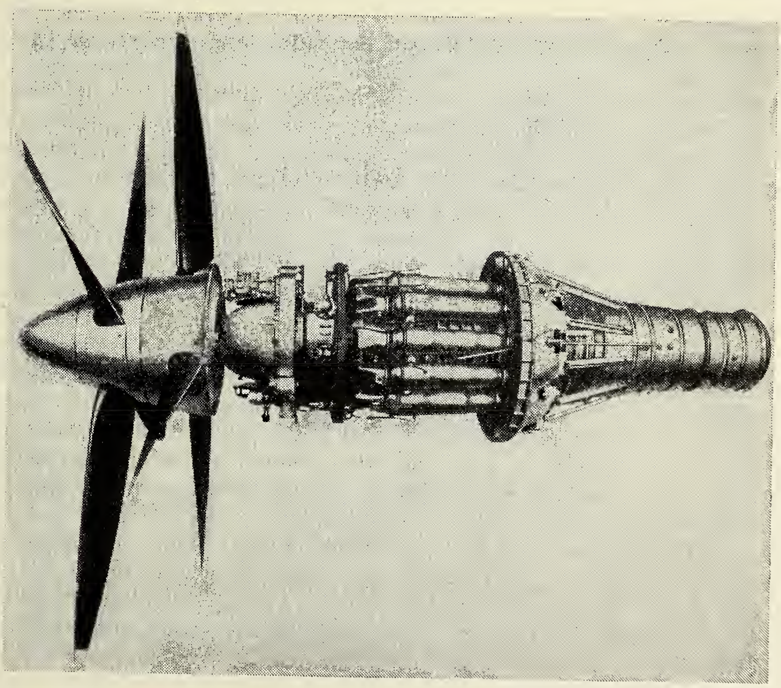
Combustion takes place in the forward third of the chamber, with the air being added to reduce temperatures from 2000°C near the burner to not more than 790°C at the turbine.

Specifications and data on the Goblin II are shown in the table on page 86.

Engineering Notes on the Armstrong-Siddeley ASX, SPI-1 and SPI-2 Python

Armstrong-Siddeley's ASX is an unusual engine, in that it is a reverse-flow axial unit, for air is taken in through 11 ports toward the shaft aft of the combustion chambers, turned 90 deg toward the upstream end, put through the 14-stage compressor, then turned 180 deg outward by radial guide vanes and into the 11 combustion chambers, through extension pipes, and turned slightly inward again before going through the two-stage turbine.

SPI-1 and SPI-2 are both propjets using the basic ASX design but with a redesigned turbine to give necessary shaft power. The SPI-1, with an over-all



Armstrong-Siddeley A.S.P. Python propeller/turbine produces 3,670 shp, 1,150 lb jet-exhaust thrust. During 1946, 25-hr type test runs were completed; and flight testing in an Avro Lancaster began in 1947. The Python is the most powerful turboprop to have reached the flight-test stage. It has been suggested as the power plant for the big Saunders-Roe S/R 45 flying boat. (*Courtesy of Skyways.*)

diameter of 54.5 in., has an annular air intake located behind the contrarotating propeller spinner; whereas SPI-2, with a 48-in. diameter, has two ducts, which could be used with a wing installation.

The ASX compressor rotor consists of two forged-aluminum-alloy sections bolted together between the low- and high-pressure stages, *i.e.*, between the fifth and sixth stages. The front shaft, of steel, is bolted to the rotor and provides accessory drive and starter-motor connections. The rear shaft, also of steel, is connected through a splined sleeve to the turbine stub shaft, which bolts to the turbine disk through a ring of studs.

Four bearings are used, two angular-contact ball units at the front, and one ball and one roller bearing at the rear. Bearings are cooled by air—that for the turbine bearings being bled from the fifth compressor stage, and that for the turbine bearings being taken off at the seventh stage.

From the compressor, the air goes through the diffuser casing, the main portion of which contains concentric diffuser vanes. From the diffuser, the air is taken into the combustion chambers through 11 elbows, which contain separate vanes. Each elbow has a blowoff valve, used to release part of the air to the atmosphere as a starting aid and to facilitate acceleration by preventing stalling of the compressor blades. On the Python, the individual valves have been replaced by a single unit on the front of the compressor casing. In both cases, however, the valve control is from a lever in the cockpit.

Combustion chambers consist of stainless-steel outer casings and flame tubes of Nimonic-75. High-pressure spray jets vaporize the fuel, rather than atomize it, toward the upstream end. A mixing chamber at the head of the flame tube takes approximately 20 per cent of the total air for primary combustion, which occurs in the flame-tube nose—with a fuel-air ratio of approximately 15:1. The burning gases then flow back over the mixing chamber, helping to heat and vaporize new fuel being pumped in. Some of the secondary combustion air enters through a hole in the nose of the flame tube, which contains a delector plate which directs the cold-air stream over the inner surface of the dome to prevent carbon formation in the rich-mixture combustion area. The remainder of the air enters the combustion chamber through perforations in the rear half of the inner chamber and by four shovel-like scoops attached to the outer casing just to the rear of the flame-tube exit.

The hot gases then go into a manifold to be reformed in an annular area just ahead of the turbine, which has two sets of blades set in the one disk by serrated Christmas-tree roots.

The fuel system includes a variable-stroke Lucas pump incorporating a maximum-speed governor and maximum-pressure-relief valve. In the Python, the fuel and control system are controlled by a single pilot's throttle lever, which selects the proper pitch and speed; measures the correct amount of fuel; and makes automatic corrections for altitude, speed, and temperature.

Accessories, which are set behind the propeller spinner, include starter motor; tachometer; propeller constant-speed unit; oil pumps, both pressure and scavenge; combined auxiliary oil-pressure metering and scavenge pumps; fuel pump and governor; barostat; fuel shutoff valve; fuel filter; ignition jet-control valve; ignition coils; blowoff valve control; and exhaust temperature controls.

ASX and Python Specifications and Data

	ASX	SPI-1
Thrust, static sea level	2,600 lb	1,150 (plus 3,670 shp)
Maximum rpm	8,000	8,000
Thrust, cruising (7,600 rpm)		950 (plus 2,720 shp)
Weight, dry	1,900 lb	3,010 lb (SPI-2 — 2,980 lb)
Weight, installed		4,100 lb (SPI-2 — 2,980 lb)
Length	168 in.	136 in.
Maximum diameter	42 in.	54.5 in. (SPI-2 — 48 in.)
Compression ratio	5.5:1	5:1
Combustion chambers	11	11
Fuel consumption, take-off	1.03-lb/hr/lb thrust	
Fuel consumption, cruising	1.0-lb/hr/lb thrust	
Oil consumption		0.5 gph (SPI-2)

Engineering Notes on the Metropolitan-Vickers F3

Thrust augmentation through use of contrarotating fans is among the latest British turbojet developments just revealed.

The new unit, developed from the Metropolitan-Vickers F2, is designated F3 and develops, from the straight hot jet, 2,400 lb static sea-level thrust for a weight of 1,650 lb and, with the fan augmentation, a thrust of 4,000 lb for a weight of 2,200 lb. This gain in thrust is accomplished without any fuel consumption increase, the result being that the engine has a specific fuel consumption of 0.65 lb per hr per lb thrust.

Basically, the air flow is simple: through a nine-stage axial-flow compressor; into an annular combustion chamber; through a two-stage turbine driving the compressor; through two two-stage contrarotating turbines driving two fans; then on out separate exhausts, the two streams joining at the jet-pipe end.

Unlike most axial-flow compressor casings, which are symmetrical in shape, that on the F3 has a larger diameter at the intake than at the turbine end. It is built in four sections which bolt together along axial flanges and a circumferential flange at the sixth compressor stage.

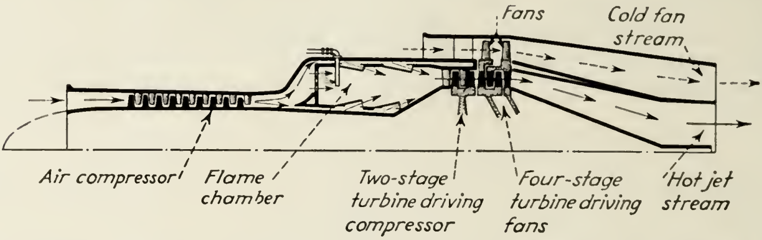
The starter motor and oil pumps are housed in a spinner type of fairing at the intake end, with the air entering the annulus between faired spikes and four concentric rings forming a grid. Other accessories are mounted atop the compressor casing, the drive being from a vertical shaft set just ahead of the front thrust bearing.

The drum of the compressor is a single-piece forging with machined serrated slots in the outer surface taking the turbine-blade roots, which are spaced by distance pieces and peened in place. There are 68 blades in each compression stage, and the blades are all similar in design.

Bolted to a flange inside the compressor drum at the third stage is a conical diaphragm, the apex of which is attached to the front thrust bearing, the diaphragm being splined to transmit power through a quill shaft to the accessories.

Also bolted to a flange at the downstream end of the compressor drum is another, but more elongated, cone which extends aft inside the annular combustion chamber, ending in an internally splined sleeve that runs in the turbine bearing and houses the turbine shaft.

At the upstream end of the combustion chamber, a deflector ring divides the air into two annular streams, directing most of it around the flame tube, which is housed concentrically within the chamber. Both inner and outer walls of the chamber contain 80 wedge-shaped inlets that are set in two staggered rows of 20 inlets each to admit the air into the flame tube downstream from the burners. Just downstream from the deflector ring is a circumferential end plate pierced by rings of small holes to meter and set up



Cross-section sketch of F/3 shows flow of air through nine-stage axial-flow compressor, annular-combustion chamber, two-stage compressor turbine, and 2 two-stage contrarotating fan turbines. Air streams from hot jet and fans are kept separate until they reach jet orifice. (*Redrawn from Flight.*)

turbulence in primary air from the compressor. Burners are plain, shrouded tubes set 18 deg apart, with nozzles forcing fuel upstream at 650 psi.

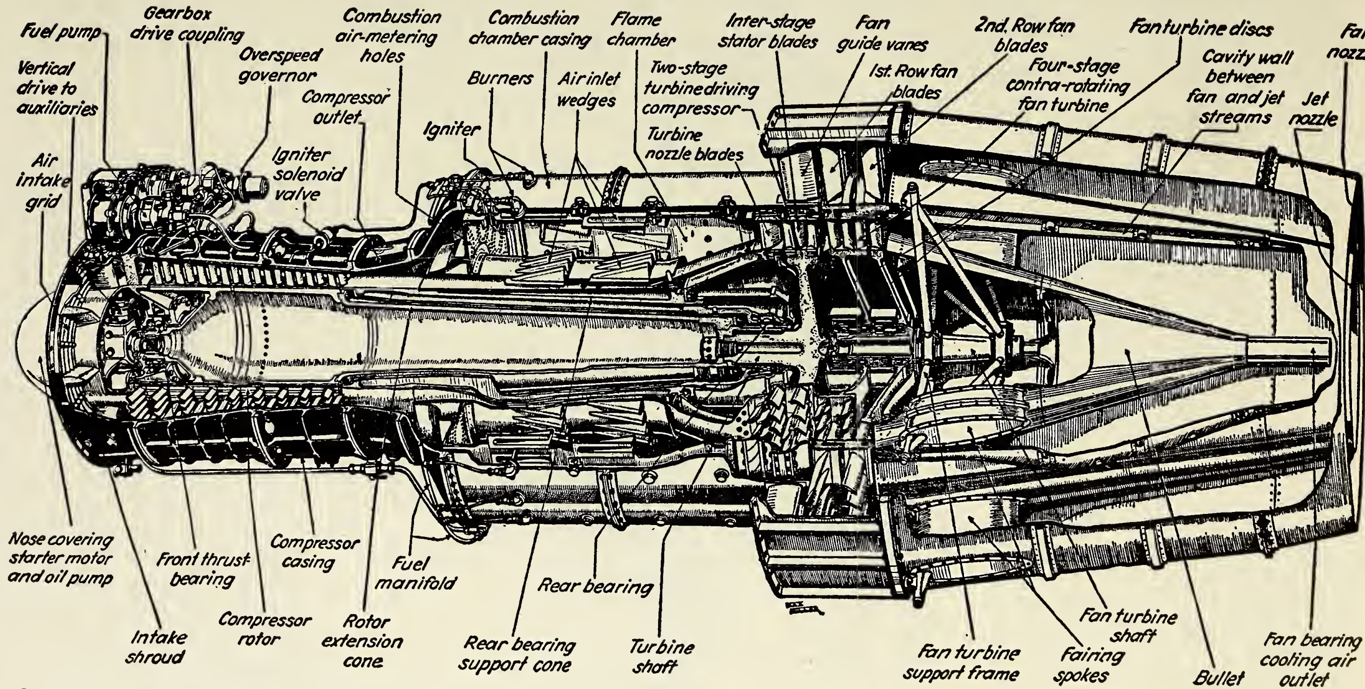
The combusted gas then moves through 56 turbine-nozzle vanes, through the first stage of the compressor turbine—which has 80 blades—then through a ring of 84 stator blades and through the second stage of the turbine compressor.

This compressor turbine has a single disk with a T-shaped rim supporting both rows of blades which are anchored by bulb-type roots locked in place by peening.

Immediately downstream from the turbine compressor are two contrarotating two-stage turbines for driving the fans. Disks of both fan turbines are swept forward, to allow room for bearings at the hub and to get the blades close to the compressor turbine. Each fan turbine is carried on a pair of roller-and-ball thrust bearings, both sets running on a common shaft supported by a six-point tubular brace, which also supports the far ducting and jet cone.

The first row of blades of the first fan turbine is set just forward of the disk, with the fan blades being mounted on a shoulder extending out from the blade tips. The second is mounted on the downstream edge of an extension of the disk rim. The downstream row of the second fan turbine's blades are set in the rim right over the disk, with the upstream row being supported from the outside by a crown extending forward from the second-row blade tips, this shoulder also supporting the second row of fans.

Thus, the four rows of fan-turbine blades are nested, with one row of each being interposed between the rows of the other. Since the blades are contra-



Cutaway view of the Metro-Vickers F3, which is the F2/4 with a four-stage ducted-fan thrust augmenter, a highly promising development. (*Courtesy of Flight, London.*)

rotating, the need for stator blades is eliminated. The first row of fan blades rotates at 2,850 rpm; the second, at 2,300, when the compressor turbine is turning at its maximum of 7,600 rpm.

Air intake for the fans is an annulus, with inlet guide vanes located over the turbine compressor, and has an over-all diameter of 48 in. Air from the fans is exhausted through an annular, tapered throw which surrounds the jet-gas stream but is separated from it by a double-skinned wall, which keeps the two air streams isolated until they meet at the jet orifice.

Cooling air—some of which is also used for lubrication—is taken from the fourth, sixth, and final compression stages and from the secondary air from the combustion chamber.

Radial holes drilled in the compressor rotor at the fourth stage take air inside the rotor where it flows through the conical extension to energize an air-oil mixer to provide an oil spray for the turbine bearing. This spray is then evacuated through the cavity between outer and inner cone extensions, to be gathered in a circumferential duct around the outside of the compressor outlet, where it is vented to the atmosphere. External piping also supplies air for a similar air-oil mixer used to lubricate and cool the front bearing, the drain to the atmosphere being through a pipe inside the bottom spoke of the air-intake shroud.

Air from the final compression stage is bled through a channel between the outer and inner cone extension to the front face of the compressor turbine disk, where a deflector plate directs it toward the center of the disk, whence it flows radially outward into the jet stream past the blade roots.

Some of the supply of secondary air for the combustion chamber is bled off to cool the turbine-blade tips and both the roots and tips of the stator blades and also to cool the fuel nozzles. This latter air is taken into the shroud near the root and exhausted through ventholes near the nozzles.

Additional air is bled off at the sixth compressor stage and through the tubular members of the six-point fan-support frame to the interior of the hollow turbine shaft. Part of this air supply goes through an air-oil mixer to lubricate and cool the bearings, the remainder being used to cool the downstream face of the compressor-turbine disk and the upstream face of the forward fan-turbine disk. Spray from the fan-turbine bearings is exhausted into the tail-cone bullet, escaping into the jet stream at the jet orifice.

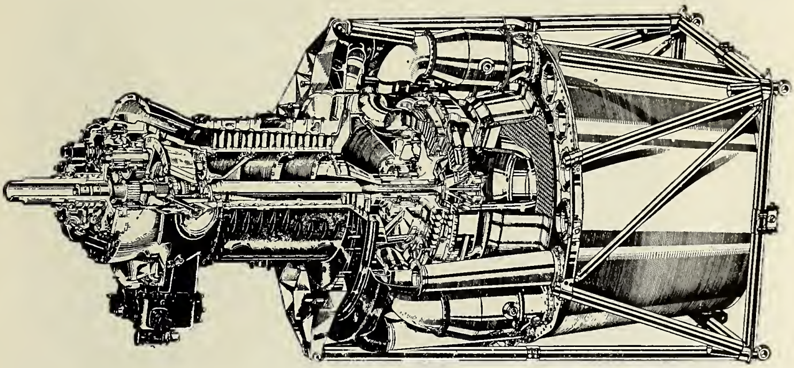
F3 Specifications and Data

Thrust, maximum sea level, with augmentation	4,000 lb
Thrust, maximum sea level, jet alone	2,400 lb
Weight, with augmentation	2,200 lb
Weight, jet alone	1,650 lb
Specific fuel consumption, with augmentation	0.65 lb per hr per lb thrust
Thrust/frontal area, jet alone	321.5 psf
Thrust/frontal area, with augmentation	318 psf
Maximum speed, turbine compressor	7,600 rpm
Maximum speed, first fan turbine	2,850 rpm
Maximum speed, second fan turbine	2,300 rpm
Length	13 ft
Maximum diameter, with augmentation	48 in.

The F3's fuel system is conventional, the fuel flowing from the tanks to a low-pressure filter to the suction side of the engine-driven pump, which sends it to the throttle valve. From here it is taken to a centrifugal governor and then to the main high-pressure valve and the manifold. The now usual barostat to regulate fuel flow according to altitude is used, being fed by a line from the pump. Another line, taken off just before the throttle valve, supplies a solenoid and two starting igniters set just off center at the top of the combustion chamber.

Engineering Notes on the Bristol Theseus Turboprop

Developed especially for long-range transport craft of 300- to 400-mph speeds, the Bristol Theseus I turboprop is a combination nine-state axial and



Cutaway view of the Bristol Theseus propeller-turbine engine with a nine-stage axial-cum-centrifugal compressor, eight combustion chambers, and a two-stage turbine. About 80 per cent of the power turns the airscrew, the balance is for jet reaction. (*Courtesy of Bristol Aeroplane Co. Ltd.*)

single-stage centrifugal compressor unit, said to be the first aircraft application utilizing a heat exchanger.

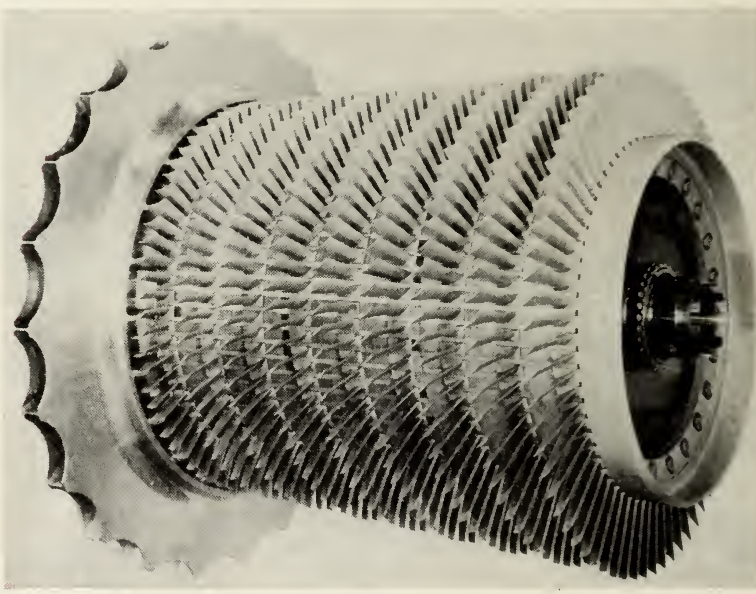
The design target was a unit that would give fuel consumption comparable to that of a piston engine at 300 mph at 20,000 ft but one in which stresses had been kept low enough to ensure long service between overhauls.

Briefly, the air flow is as follows: first through the axial compressor and then through the centrifugal unit, resulting in an over-all compression ratio of about 5:1 at 20,000 ft; then through the heat exchanger, in which temperatures are raised by exhaust gases; then through the combustion chambers to a two-stage turbine driving the compressor; then through an independently mounted single-stage turbine driving the propeller; and finally through the hot side of the heat exchanger to the exhaust nozzle.

Approximately 80 per cent of the available power is used to drive the propeller at 300 mph. "Speeds of the two turbines," according to the manufacturer, "are maintained at a constant ratio by means of an ingenious mechanism which controls the pitch of the propeller blades."

Two main reasons dictated use of both axial and centrifugal compressors: (1) The centrifugal unit is an efficient means of getting the air from the small diameter of the axial unit to the diameter necessary for the heat exchanger; (2) the producers feel that "although the axial compressor can be made to operate more efficiently at higher compression ratios than the centrifugal type, the latter had a wider operating range."

Air enters the unit through an annular intake just behind the propeller. The intake casing is an aluminum-alloy casting having inner and outer shells



Nine-stage compressor of the Bristol Theseus turboprop. (*Courtesy of Bristol Aeroplane Co. Ltd.*)

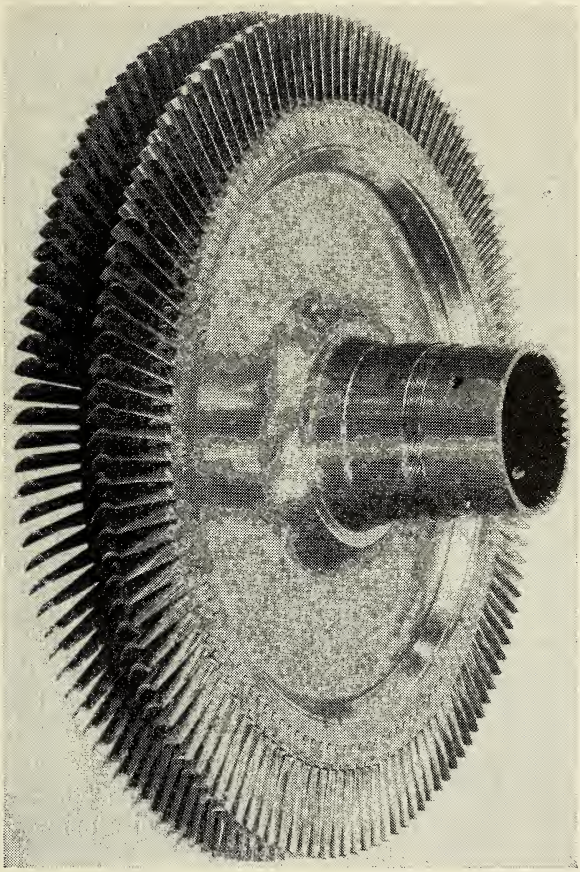
connected by eight hollow vanes. The inner shell contains propeller reduction gear and accessory drive casing, with drive shafts extending laterally to the starter motor (mounted outside the outer shell) and downward to the oil pump and sump, also mounted on the outer shell.

Aluminum-alloy compressor casing is cast in halves bolted axially and supporting the intake casing through bolts in flanges. The axial section, and part of the centrifugal section, of the compressor casing is double skinned to relieve the portions of the compressor carrying stator blades from propeller load stresses. The aft portion of the compressor casing forms the front face of the centrifugal impeller chamber and, with the delivery manifold and rear casing, forms the centrifugal stage.

The aluminum-forging axial compressor is of drum construction, made up of three identical sections to simplify production and assembly. It is bolted to two conical steel shafts, the front one being carried by a roller bearing; the rear, by a ball bearing which also supports the compressor turbine. Each

compressor stage has 69 blades, made of aluminum stampings attached to the rotor drum by axial, serrated slots.

The centrifugal compressor is machined from a solid-aluminum forging bolted to the axial rotor drum. It has 23 straight radial vanes and is double shrouded.



Two-stage turbine of the Theseus propeller-turbine engine. (*Courtesy of Bristol Aeroplane Co. Ltd.*)

At full throttle, the compressor runs at 8,200 rpm, delivering 20 lb per sec air to static sea-level conditions, requiring approximately 3,500 hp.

The delivery manifold is a one-piece magnesium casting in which the compressed air is sent to the two-piece magnesium-casting diffuser-vane ring, which passes the air to the cold side of the heat exchanger through eight transfer pipes spaced around the engine between combustion chambers.

Of matrix construction, the heat exchanger consists of hundreds of straight tubes set axially to offer the least resistance to passage of the hot gases.

These tubes are arranged in 16 sets—8 outlet and 8 inlet—each group being separated by headers. Going through the exchanger, the air is first headed radially inward, then reversed to the outlet headers.

Weight of the heat exchangers is given as approximately 500 lb and "requires some several hours' flying in order to save its own weight in fuel, and this factor makes the heat-exchanger version of the Theseus essentially a long-range power plant," according to Bristol reports. "This does not mean, however, that it cannot also be used on shorter journeys, since the heat exchanger can be omitted, resulting in a power plant's having a slightly increased fuel consumption but with a considerably decreased weight. The fuel consumption even without the heat exchanger is very much less than that of contemporary jet engines and still of the same order as for reciprocating engines of similar power."

Sheet-metal combustion chambers are of standard design, and provision is made for entry of cooling air to keep temperatures down.

From the combustion chambers, the hot gases are delivered to the 48 first-stage nozzles through a tangential delivery manifold to the two-stage compressor and accessory turbines. The compressor turbine has a single wheel, the two sets of blades being mounted on a rim shoulder by Christmas-tree serrated slots. The turbine disk is of forged heat-resistant steel with an integrally forged hollow hub, which is splined to transmit power to the compressor shaft. Blades are forged from precision castings.

From the compressor turbine, the hot gases go through a third stage of stator blades—also forged from precision castings—to the single-stage propeller-driving turbine, which has a maximum speed of 9,000 rpm. The disk is a Stayblade forging with an integrally forged stub shaft going to the rear bearing. The propeller drive shaft bolts directly to the front face of the disk and extends upstream through the compressor turbine and inside the compressor drum to the 8.4:1 epicyclic reduction gear.

The turbine casing is made up of three steel castings, the third-stage casing also providing support for the propeller turbine's rear bearing through eight radical vanes similar to that in the intake casing.

Theseus Specifications and Data

Length	106 in.
Diameter	48 in.
Dry weight	2,130 lb
Propeller speed (maximum power)	1,070 rpm
Power, static sea level	1,950 bhp + 500-lb jet thrust
300 mph, sea level	2,300 equivalent bhp [1]
300 mph, 20,000 ft	1,500 equivalent bhp
Fuel consumption, maximum power, sea level	0.57 lb/equivalent bhp/hr
maximum power, 300 mph, 20,000 ft	0.50 lb/equivalent hbp/hr

[1] Equivalent bhp defined as propeller-shaft hp + jet hp/propeller efficiency.

The Theseus has six main bearings—two each carrying the compressor assembly, the propeller shaft, and the propeller turbine drive shaft. The rear compressor and rear turbine bearings are single-row ball units, which also absorb thrust. The rear compressor bearing also absorbs some thrust but not a great deal, since the compressor and turbine thrusts are balanced as closely as possible.

CHAPTER FOUR

The AAF and American Industry Pull a Miracle

THE KEY TO the recent rapid progress in turbojet engines has been the development of metals to withstand the high temperatures and stresses to which the combustion chambers, turbine-guide vanes, and turbine blades are subjected. As this was also the key to the AAF's turbosupercharger program, it will be necessary to glance at it briefly if a correct perspective is to be gained.

The turbosupercharger and turbojet may be regarded as birds of a feather, since they both convert hot gas into mechanical work through a turbine. The difference is that the turbojet generates its own heat and converts it into thrust, whereas the turbosupercharger depends on the conventional engine for its supply of hot exhaust gas and may be so installed that some jet thrust is developed by the gases as they are exhausted. The turbines of both must withstand very high temperatures under extreme centrifugal stress. Both drive compressors directly from the turbine shaft. But the air compressed by the turbosupercharger is ducted back to the carburetor of the conventional engine to keep it operating at sea-level power, whereas the compressed air of the turbojet unit is ducted into a combustion chamber, where its temperature is increased by combustion of the fuel. In either case, on reexpansion of the hot gases, sufficient energy is used by the turbine to drive the compressor and accessories; the energy remaining in the gases is used to produce a high-velocity jet. Thrust is developed through reaction to this high-velocity discharge.

For nearly a quarter of a century, America's leading industrial metallurgists have been concentrating research on development of alloys that could withstand constantly higher temperatures and greater centrifugal stresses. This search for high-temperature alloys was stimulated primarily by the AAF development program for the turbosupercharger. The program was kept alive by a handful of men who refused to lose faith when time after time, as a result of high-temperature operation, the turbosupercharger would throw its blades out of the turbine. These men knew that the problems in the turbosupercharger were giving them the answers that

would eventually pave the way for successful development of an efficient gas turbine for aircraft propulsion.

Basic research in the hunt for high-temperature alloys goes back to World War I and to the late Dr. Sanford A. Moss, gas-turbine expert for the General Electric Co., one of the nation's largest turbine manufacturers. As early as 1902, Dr. Moss, while at Cornell, operated a turbine wheel

The inventor of the turbosupercharger, Dr. Sanford A. Moss, consulting engineer at the General Electric (Lynn, Mass.) Works, explains to "Jimmy" Doolittle that a turbosupercharger is just a gas turbine which, by compressing the air, enables aircraft engines to "breathe" at high altitudes. (*Courtesy of General Electric Co.*)

from the products of combustion, under pressure. He also designed a simple type of gas turbine to compress air for high-altitude operation. This was the turbosupercharger. Under sponsorship of NACA—of which more later—Dr. Moss first had explored the 1917 turbosupercharger of the Frenchman Rateau, after which he came through with the basic turbosupercharger as the AAF knows it today.

The first altitude test of this turbosupercharger was atop Pikes Peak—14,109 ft above sea level—in the late summer of 1918. On a specially rigged dynamometer test stand, it was hooked up with a 350-hp Liberty engine. Without the turbo the engine turned out only 230 hp, but with it, even more than the sea-level power—356 hp—was obtained. One year

later (September, 1919), Maj. R. W. (Shorty) Schroeder took a LaPere biplane to 18,000 ft, using the new turbo. Less than six months later, Major Schroeder successfully flew to 33,160-ft. altitude, where his oxygen supply failed. His plane plummeted, but he regained consciousness and pulled out at 2,500 ft.

These flights were precarious, because equipment had not yet been perfected for such altitudes; but the turbo performance was so encouraging that, despite dwindling appropriations, developments were carried on by General Electric, largely through the zeal of an ex-Army man, A. L. (Doc) Berger.

Parts being used for the turbosupercharger were principally steel until the introduction, in 1922, of Silchrome No. 1, a chrome-nickel-molybdenum alloy, which could withstand high stresses at temperatures over 1100°F. This was used for the turbine disk until 1937 and for turbine blades until 1928. A British alloy, KE-965, with a 1,200- to 1,400-deg operating range was used for blades from 1928 to 1933. In that year, the Cyclops Steel Co.'s alloy was adopted for blades, since it could operate at higher temperatures; and in 1937, this alloy was adopted for use in turbine disks.

Later developmental programs led to the production of an alloy for blades by the Haynes-Stellite Co. (Hastelloy B), of Timken alloy for turbine disks by the Cyclops Steel Co., and of Vitallium—all capable of operating with gas temperatures in excess of 1500° F. By 1939, these high-temperature alloys were operating satisfactorily in the turbine wheel; and up to the end of World War II, they were being used in GE turbos to supercharge the engines of our Boeing Superfortresses and fighter planes at altitudes above 30,000 ft when required and are also being used at the present time for buckets and wheel disks in our turbojet engines. (For a more complete discussion of metallurgy and the gas turbine, see Chapter Seven.)

By 1939, however, when higher temperature alloys were available, Doc Berger had switched his attention to a program for developing the gas turbine as a prime mover. America's first official military interest in jet propulsion for aircraft was expressed in 1922, when the engineering division of the U.S. Air Service at McCook Field (predecessor of Wright Field) requested the Bureau of Standards to investigate the practicability of jets. (A. L. Berger received the Thurman H. Bane award for 1947.)

This study, prepared by Edgar Buckingham and later published by NACA, concluded that "propulsion by the reaction of a simple jet cannot compete, in any respect, with airscrew propulsion at such flying speeds

as are now in prospect." Such flying speeds were envisioned as 250 mph, and computations indicated that at this speed the jet would take about four times as much fuel per thrust horsepower as the airscrew.

Accordingly, further investigations were held in abeyance until the fuel consumption of such units could be reduced through increased efficiency of jet-engine compressors and turbines—also, until aircraft speeds were increased to the point where a reasonable propulsion efficiency could be realized. A major factor in the efficiency of jet engines was ability to operate at extreme high temperature; and during the next 15 years, as we have seen, such progress was made in the development of heat-resistant alloys that the gas turbine could operate hot enough and be made light enough so that its use as the power plant of an aircraft became a practical possibility.

Despite a starvation diet in the matter of research and development, a modest program was launched by the Army Air Corps at Wright Field in 1938, with 1943 as a goal for perfection of the gas turbine as a supplement to the conventional reciprocating engine in aircraft. As we have seen, the British developments were under way by this time, and the German preliminary work had also begun. The Wright Field program was under the direction of Col. E. R. Page, chief of the Power-Plant Laboratory until 1943, when he switched to jet developments at the NACA Engine Laboratory in Cleveland. Under him were spark-plug Doc Berger and Opie Chenoweth, veteran civilian engineering executive of the Wright Field Power-Plant Laboratory. What they have meant to the country and civilization was well summarized by Colonel Page, when he said, "This team of the ingenious mechanic [Berger] and the technical expert [Chenoweth] is one of the nation's best. Although Doc wasn't an engineer in the academic sense, he always could depend on the technical assistance of Chenoweth, who had the knack of channeling Doc's development work along sound engineering lines without discouraging his inventive genius."

First step in the Air Corps program was to issue a contract to General Electric for a two-stage turbine, a contract that might be construed as preparing the way for the production of the turbojet engine 2 years later. Next, in 1940, a contract was awarded to Allis-Chalmers Mfg. Co. for development of a two-stage turbine that could be geared to the drive shaft of a conventional engine, applying some of the turbine power to the propeller. This adaptation, known as the "compound engine," was another Berger-Chenoweth step in the direction of the harnessing of gas-turbine power. Though little has been heard of the compound engine, it has become an outstanding development, as will be seen in a later chapter (see page 196).

America's jet-propulsion program was accelerated early in 1941, when General Arnold, who had been much interested in the subject, called for reports on the state of developments on aircraft gas turbines in this country and England. A few weeks later, during a stay in England, he had an opportunity to examine at first hand the Whittle engines and other research and development projects on gas turbines and jet propulsion for aircraft. At that time, Col. (later Brig. Gen.) A. J. Lyon was General Arnold's representative in England for all technical matters. General Electric had sent D. Roy Shoults, a senior staff member of the gas-turbine division, to England to assist Colonel Lyon in the early stages of his association with the British Ministry of Aircraft Production (MAP) in connection with the servicing and use of turbosupercharger equipment.

General Arnold arranged with Sir Charles Portal, marshal of the RAF, and with MAP that all information on the Whittle jet engine be made available to his technical staff in London so that a report might be forwarded to the United States for further study and the formulation of a production program. He felt that this would greatly benefit the common cause by utilizing United States technology regarding heat-resistant metals resulting from the development of the turbosupercharger, and production facilities in this country, far beyond the reach of German bombers.

Returning to the United States in May, General Arnold put the bee on Brig. Gen. Frank Carroll, chief of the engineering division, Wright Field, and on Brig. Gen. Oliver P. Echols, A-4 on the Air Staff at AAF headquarters in Washington, to get ready for the technical and production blitz which was shortly to be on the way. He also approached the State Department, and a series of negotiations on the Hull-Halifax level was begun. After several weeks, an agreement was reached whereby the United States was to receive from England the complete drawings, the production rights, and especially the actual Whittle engine, which had been successfully test-flown in the Gloster experimental fighter. At the same time, the Portal-Arnold gentlemen's agreement was made whereby, at appropriate times in the future, information to the public on the subject of jet propulsion for aircraft would be released only after joint consultation.

When this was settled, General Arnold appointed Shoults to act with Colonel Lyon as an investigating committee to report on the technical aspects of the Whittle jet engine. Maj. (later Brig. Gen.) Carl Brandt was requested by Colonel Lyon to act as a member of the committee to report on the technical aspects of the test airplanes. Preliminary discussions among Colonel Lyon, Shoults, and Major Brandt, on the one hand, and Air Marshal Linnell of MAP and Dr. Roxbee Cox of Power Jets, on the other, were begun on July 22, 1941, and were followed by visits to

the Power Jets research laboratory, discussions with Frank Whittle (then a wing commander), and visits to the Gloster works, where they had consultations with George Carter, designer of the E28/39 and the Meteor.

In the meantime, Maj. (later Col.) Donald J. Keirn left his engineering post at Wright Field and late in July reached England on a hush-hush mission. When he arrived, he found that he had been appointed by General Arnold to be Colonel Lyon's deputy for the entire aircraft gas-turbine project. Group Capt. G. E. Watt was appointed by the British to be Major Keirn's opposite number, and between them they carried out a classic piece of transatlantic cooperation. (On Nov. 9, 1944, at a meeting of the IAS, New York, Colonel Keirn received the Thurman H. Bane Award for 1944 for his "contribution to the development and utilization of the jet-propelled engine.")

Back on this side of the Atlantic, on Sept. 4, 1941, an initial conference was held in General Arnold's office at AAF headquarters to hear Shoults' presentation of the London investigating committee's recommendation for a United States program and to determine the feasibility of going into immediate production of the Whittle engine. It was also necessary to determine which airplane manufacturer was at that time best qualified to carry out the jet-propulsion development in conjunction with General Electric, which had had extensive experience with steam turbines and turbosuperchargers.

Among those present at the conference were Robert A. Lovett, Assistant Secretary of War for Air; (the then) Brig. Gen. Carl A. Spaatz, Chief of the Air Staff; (the then) Brig. Gen. Oliver P. Echols, Chief of the Matériel division (A-4); his assistant, Col. (now Maj. Gen.) Benjamin W. Chidlaw; Maj. Carl Brandt; and Messrs. D. R. Shoults, R. C. Muir, Dr. A. R. Stevenson, Jr., and S. R. Puffer of General Electric. After examination of the preliminary data, drawings, and blueprints flown back from England by Major Brandt and assembled by Shoults, the General Electric engineers agreed that it would be possible to produce a duplicate engine within 6 months, with two more engines in an additional 2 months, the latter two engines to be flight articles. It was further decided to invite Lawrence D. Bell, president of the Bell Aircraft Corp., to Washington the following morning.

Accordingly, next day, Larry Bell, H. M. Poyer, then Bell's chief engineer, and Shoults reported at General Arnold's office. After discussion, it was agreed that in line with the recommendation of Colonel Lyon's investigating committee, General Electric would build 15 of the Whittle-designed turbojet units from the British drawings and that Bell Aircraft would build three twin-engined fighter aircraft designated as "XP-59A."

Bell and General Electric were to work in close collaboration. The contracts, under absolute secrecy, were prepared by (the then) AAF Matériel Command. Major Keirn (at that time still in England) was named as project officer, in addition to his duties as liaison officer between the AAF and MAP.

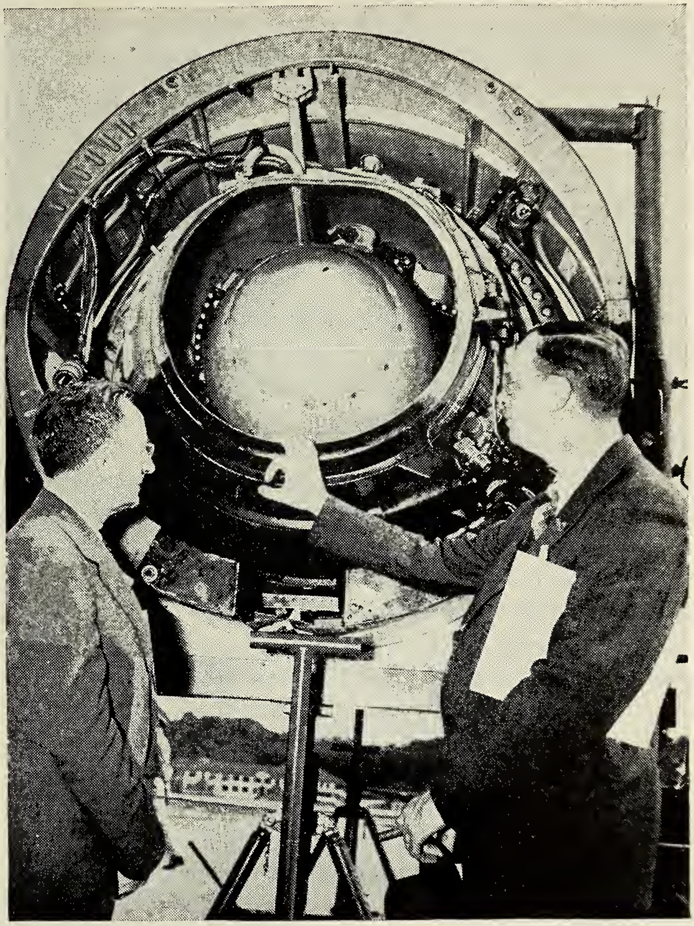
General Arnold turned over to GE the sketches that Shoults presented at this preliminary meeting, and the company immediately got to work

Photograph by F. Lumbers, Leicester

The Power Jets team that flew to the United States in early October, 1941, with the then Maj. Donald J. Keirn with a Whittle W1X jet engine and drawings of the W2B to assist General Electric engineers in the manufacture of the latter. *Left to right:* Flight Sgt., now Warrant Officer, J. A. King, RAF (attached to Power Jets, Ltd.); Mr. D. N. Walker, chief test engineer; and Mr. G. B. Bozonni, head test fitter. The W2B was the basis of the Type I-A jet engine.

on the Whittle type of engine. Test facilities were ready for Major Keirn and a small team of Power Jets engineers when they came to the United States on Oct. 2 with complete sets of blueprints of the improved W2B unit and the actual W1X Whittle engine concealed under improvised floor boards in the bomb bay of a Consolidated B-24 Liberator. (The W1X was the engine first installed in the Gloster E28/39 for taxiing trials in April, 1941.) The Power Jets team consisted of D. N. Walker, chief test engineer; G. B. Bozzoni, experimental fitter; and Flight Sgt. J. A. King, RAF. General Electric set up shop in its old enameling building at West Lynn, Mass., with a staff of 30 supercharger experts headed

by Reginald G. Standerwick, chief of the supercharger engineering division, and S. R. Puffer. Donald F. (Truly) Warner was in active charge of jet-engine design and development. (This may be as good a place as



General Electric's Reginald G. Standerwick (*left*), chief of Supercharger Engineering Division, and Donald F. (Truly) Warner (*right*), in charge of jet-engine design and development, examine an I-16 (J-31-GE) Whittle-type turbojet engine.

any to point out that the highly successful development of the aircraft gas turbine with *centrifugal* compressor was entirely the work of an RAF-AAF team in close cooperation with units of British and American industry.)

Within less than the stipulated 6 months from Sept. 5, 1941, the first

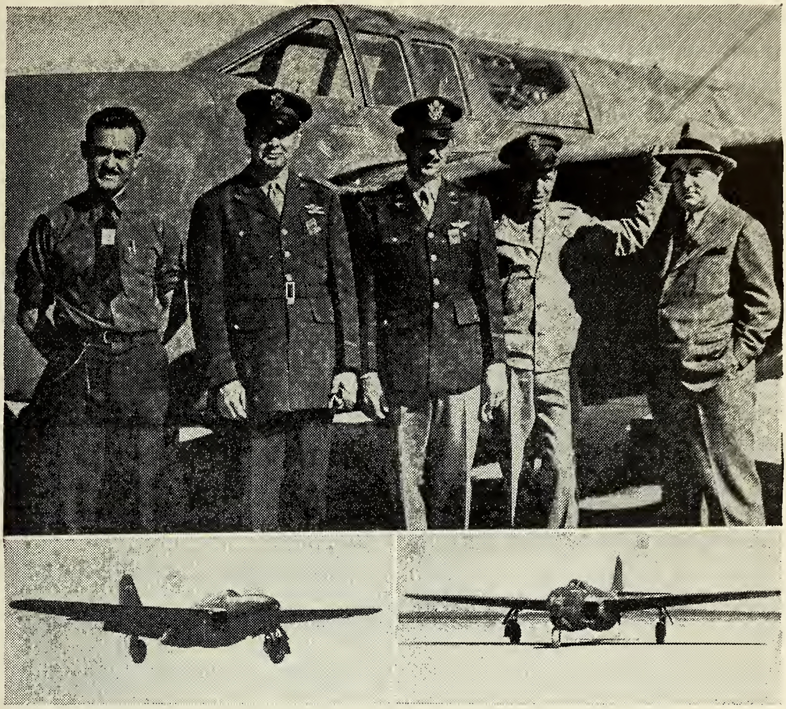
production unit was completed. There were many bugs to eliminate; but by Mar. 18, 1942, or 28 weeks after the work began, the first successful test run was completed. The "Type I" turbojet, except for routine changes to adapt the unit to GE shop practice and a few minor mechanical refinements, was practically identical with the Whittle unit. (Later units were designated "I-A" and embodied many design changes by General Electric's turbine experts to increase the thrust and to improve efficiency through the use of the turbosupercharger alloys developed in this country during the past two decades.)

America was still a long way from quantity production and did not have a successful experimental model of a turbojet engine for its proposed jet airplane, so that producing it in such a short time may be regarded as one of the engineering miracles of the war.

The work had to be so carefully guarded that when Whittle came to this country in May, 1942, with drawings for the advanced W2/500, he registered at the Statler Hotel in Boston as Whitely and had a private telephone line installed and a special waiter and bell captain assigned to his room. He later moved into Standerwick's house in Swampscott; and during the 3 months of his stay, conversation was so cautiously guarded that not even Mrs. Standerwick knew the identity of her guest or the true nature of his work.

In the meantime, Larry Bell had rented office space in Buffalo for the secret project; and Poyer selected a small group of experts from his engineering staff, swore them to secrecy, and transferred them there. Within two weeks, they had whipped up the outlines of a design comprehensive enough to show General Arnold and get a green light from Maj. Gen. Benjamin W. Chidlaw (who was then chief of the engineering branch on General Echols' staff), who had been appointed liaison officer on the project, coordinating activities at Bell and General Electric with the British and Washington; Roy Shoults was his opposite number in the industry. (He later went with Bell Aircraft and is now chief engineer at Glenn Martin's.) Approval was also obtained from Maj. (later Col.) Ralph P. Swofford, Jr., who was aircraft project officer at Wright Field, teaming up with Major Keirn, who was the jet-engine project officer. Both were under Brig. Gen. Frank O. Carroll, chief of the engineering division.

Within three months of the awarding of the contract, the major elements of the experimental jet fighter were so far along that a secret factory was set up on the second floor of a loft building in Buffalo, with space enough to build the three XP-59A's. Windows were welded shut, and lower panes covered with paint. Three months later, the prototype



A group of America's pioneers in jet propulsion standing beside the Bell XP-59A. *Left to right:* Bell's chief test pilot, Robert (Bob) Stanley; Brig. Gen. Benjamin W. (Uncle Ben) Chidlaw, chief, Development Engineering, Hq. AAF; Maj. (now Col.) Donald J. Keirn, gas turbine project officer and liaison with the British; Maj. (now Col.) Ralph P. Swofford, Jr., jet aircraft project officer at Wright Field; Lawrence D. (Larry) Bell.

The XP-59A with dummy propeller (wings detached) was brought from Buffalo to Muroc (Calif.), in a well-guarded freight car, then towed to the secret jet-flight test base at Muroc Dry Lake, 5 miles away from the regular AAF bombardment base at Muroc. (*Courtesy of Bell Aircraft Corp.*)

was finished; the other two, well on the way. XP-59 had been the designation of an unorthodox earlier Bell design; it was a simple matter to substitute 59A and maintain the secrecy.

In order to find a secluded spot for the secret testing of jet aircraft, General Chidlaw and Major Swofford made a "Cook's tour" of many sections of the United States and finally, after very careful study, selected Muroc Lake, Calif., for the purpose. A self-sufficient post, with hangar, housing, and messing facilities was established. The jet-flight test base was 5 miles from the regular AAF bombardment base at Muroc and was so completely independent of it that the personnel there had no idea what was cooking at the secret base.

At about this time, Robert M. Stanley, veteran Navy flyer and chief test pilot and head of the flight-research department for Bell Aircraft, was brought into the picture. In August, 1942, he went to California to make arrangements, in cooperation with the Army engineers, for testing "the Squirt" at the secret base. Early in September, the first two GE Type I-A jet units were delivered under close guard, and they were sent on to Muroc with the greatest care and secrecy. General Electric mechanics and engineers installed the turbojets in the XP-59A. This done, the secret jet fighter was shrouded in a tarpaulin, and a dummy propeller attached to the nose before towing it to the take-off area. The ruse worked.

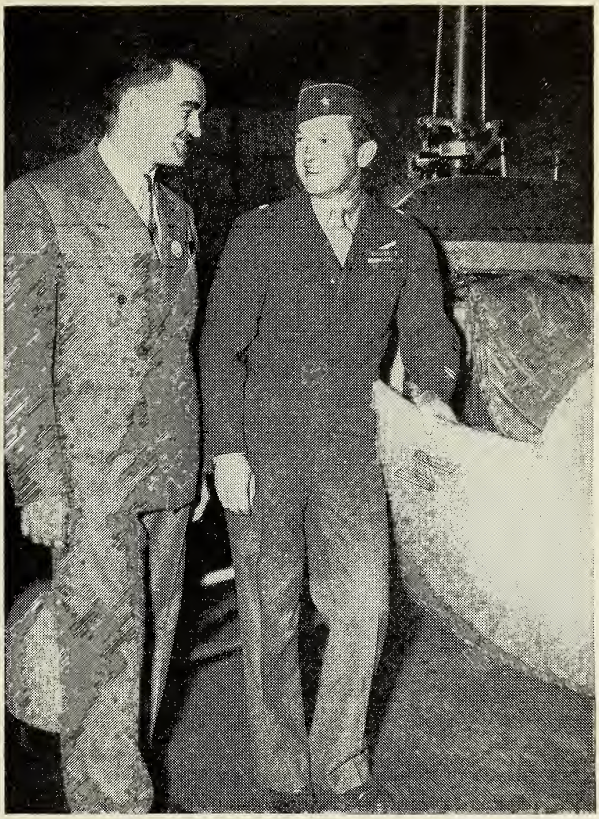
Ground tests were run, with the jet units performing smoothly; and on Sept. 29 and 30, taxiing tests were conducted. At the official test on Oct. 1, Bob Stanley, before a group of Bell and General Electric officials and engineers, Air Force officers, and aviation scientists (including Dr. Durand, chairman of NACA's committee on gas turbines and jet propulsion), flew America's first jet-propelled airplane. First flight was to a height of 25 ft, followed by a second hop to 100 ft. It was the second Allied aircraft of this type to fly.

Next day, Stanley took off again, flying to 4,000 ft, and noted: "Duration of flight, 30 min; throttle was applied promptly, and acceleration during take-off appeared quite satisfactory." On his second flight, he reported: "The speed in level flight at 10,000 ft. was surprisingly high . . . I had less trouble and fewer mechanical interruptions than with any other prototype I'd ever flown."

Following that flight, Col. (later Maj. Gen.) Lawrence C. (Bill) Craigie, chief of the aircraft-project section, Wright Field, in the absence of Colonels Keirn and Swofford (then in England on further jet-propulsion projects) and General Chidlaw (fuming at his desk in the Munitions Building), took the plane aloft. Chidlaw, Keirn, and Swofford had drawn straws out of a hat to see who would fly "the Squirt" first; but in the un-

foreseen absence of all three, Craigie had the honor of being the first Army officer to fly the new jet fighter.

All the flights were successful, but tests were continued at the lonely station for about a year while the bugs inherent in any new aircraft and



The first two pilots to fly America's first jet-propelled airplane, the Bell XP-59A, at the secret testing base of Muroc Lake, Calif. Bell's chief test pilot, now chief engineer, Robert M. Stanley, took it on its maiden flight, Oct. 1, 1942; the next day Col. (now Maj. Gen.) Lawrence C. (Bill) Craigie became the first Army officer to fly the experimental jet fighter. The two are shown here at a meeting in April, 1945, during flight tests of an early helicopter. (*Courtesy of Bell Aircraft Corp.*)

engine design were exterminated. The jet engine, being of a highly experimental type, naturally received the major amount of attention in this respect. The three XP-59's and all but one of the 13 YP-59's were flown with the 15 I-A turbojet units originally contracted for by General Electric. Maximum speed of a conventional YP-59A powered by the I-A

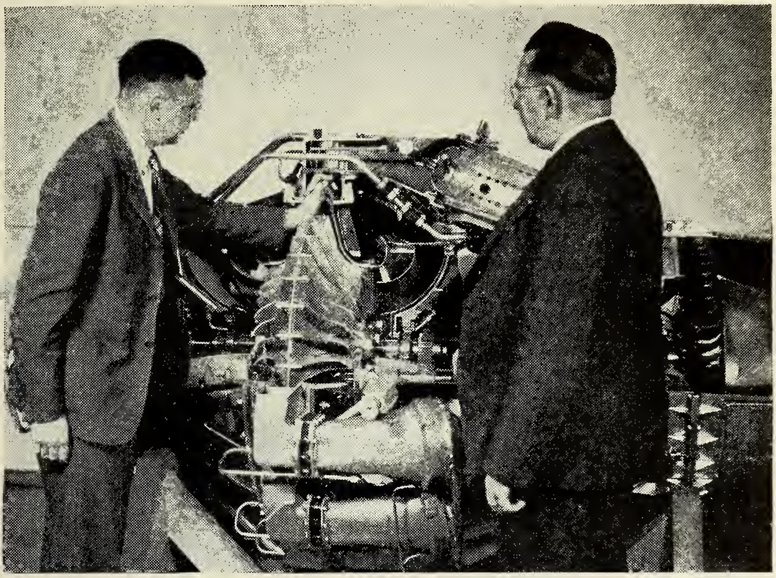
engine was 404 mph at 35,000 ft. The Type I-A unit had a thrust of about 1,400 lb. Special speed tests with a highly waxed model brought the figure to 424 mph at 35,000 ft.

By the last of April, 1943, an improved turbojet unit in the I series, known as the "I-16," was completed and on the test stand. The "I-series" designation assigned to the Whittle-type centrifugal compressor turbojets for security reasons was suggested at the first conference in General Arnold's office and arose from the fact that the original compressor and many other parts were similar to those used in the supercharger series A to F, then in production at GE. Many of the personnel employed in that production were quietly switched over to the jet-engine work, which made the adoption of an I-designation quite suitable. Most of them thought it was another turbosupercharger. (A joint Army-Navy committee in 1945 approved a new designation series, whereby the I-16 became the J-31-GE-1 and the I-40 became the J-33-GE-1, the present production model at Allison being the J-33-AL-4.)

It was expected that the use of the 1,600-lb thrust I-16 in the P-59A would add 10 to 15 per cent to the maximum speed of the XP-59A powered by the I-A unit, but a series of tests in the summer of 1943 indicated that 414 mph at 35,000 ft was all that could be squeezed out. Wright Field put the bee on General Electric to produce a larger and more powerful unit based on the Whittle design; and work on this engine, later known as the "I-40," was begun.

By late summer, war emergency ratings had increased the top speed of our conventional fighters, including the North American Mustang, Republic Thunderbolt, and Lockheed Lightning, to well above 400 mph. It was imperative that our jet fighters should have a speed of at least 100 mph more. The decision in October, 1943, was therefore to accept the P-59A as a transition jet-fighter trainer; and during 1944, it went into limited production. In this role, the Airacomet, first American jet plane to fly, was a thorough success. Colonel Homer A. Boushey, veteran pilot who has flown most of the AAF fighter planes during the past dozen years, and an all-out enthusiast for jet propulsion, came from Washington in late 1943 to take charge of the jet-training program, commanding the 412th Fighter Group. Deputy commander was Maj. (now Lt. Col.) John W. Mitchell, famed P-38 pilot of the South Pacific, who was later replaced by Capt. Tex Hill of Chennault's Flying Tigers. It was a highly selective group—nearly all aces of proved character and ability—because the 412th was to become a nest from which future jet experts of the AAF were to try their wings. As its personnel grew, and its work

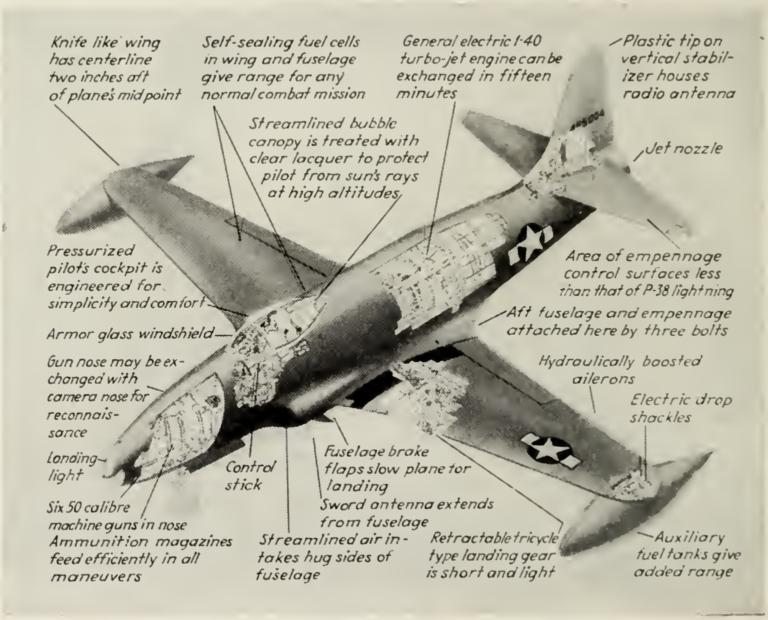
involved more and more secrecy with the advent of the P-80A, it moved successively from Muroc to Palmdale, thence to Bakersfield, and finally to Santa Maria—all in California, its present home. At the war's end, there were three squadrons—the pioneering 445th, the 29th, and the 31st—with Col. Bruce Holloway, General Chennault's chief of Fighter Command, as group commander.



Dale D. Streid (*left*), General Electric Aircraft Gas Turbine Division, and G. R. Berg (*right*), Supt. AGT Mfg. Div., with a cutaway of I-40 centrifugal-flow turbojet (now J-33), designed by Streid. (*Courtesy of Aviation.*)

In July, 1943, the Air Technical Service Command (ATSC)—then Matériel Command—handed over to Lockheed Aircraft Corporation the British de Havilland H1 and asked that a suitable airframe be built around it. Its thrust was at that time 2,300 lb, which was later increased to 2,500, then to 2,700 lb. The company's chief research engineer, Clarence L. (Kelly) Johnson, created the original design and supervised construction of the first experimental model with the aid of ATSC experts from Wright Field. The airplane was designated "XP-80." Johnson and his associates set a record for design and production, and the XP-80 was ready for flight in 180 days. On Jan. 9, 1944, the first flight tests were made, and they were highly successful. Lockheed's chief test pilot, the late Milo Burcham, was at the controls. Top speed was around 475 mph, and the rate of climb was excellent. (The XP-80 later exceeded 500 mph,

ranking with the Goblin-powered Vampire as the world's fastest airplane in the first half of 1944.) However, as additional de Havilland jet engines were not available, it was decided to predicate the production version of the Lockheed jet fighter on GE I-40, which was developed at GE's Lynn (Mass.) plant under the direction of Messrs. Puffer and Warner and Dale Streid, project engineer.



Cutaway view showing details of America's first operational jet fighter, the Lockheed P-80A Shooting Star. Allison-built General Electric J-33 (I-40) turbojet with side-fuselage air intakes provides top speed of about 580 mph.

The new version, known as the "P-80A," required substantial redesign of the prototype, in that the complete engine installation was different, the duct system changed, and the gross weight of the airplane increased by approximately 1,000 lb. The XP-80A was conceived, built, and flown in 139 days. The first test flight was made June 11, 1944; and with the increased thrust of the I-40 engine (at that time, 3,750 lb), performance of the XP-80A was substantially greater than that obtained with the original airplane. Lockheed's test pilot, Tony La Vier, put on a dazzling demonstration. Over a year later (Aug. 1, 1945), the AAF announced the top speed of the P-80A as "more than 550 mph." Colonel William Councill's record-smashing nonstop flight in a Shooting Star from Burbank to La Guardia Field in early February, 1946, lends solid support

to this claim as well as to its having a range of "more than 2,000 mi." Average ground speed was 584.82 mph, with top indicated air speed on part of the leg between Akron and New York (with 80-mi tail wind) approaching 700 mph. Elapsed time was 4 hr 13 min 26 sec.

In addition to the P-80A, the J-33 (I-40) was the power plant of the twin-jet Bell XP-83, which was test-flown in the fall of 1944 and announced in October, 1945. Although heavier than the earlier P-59A, the cleaner design and greatly increased power of the XP-83 enabled it to outperform the Airacomet by a wide margin. When operating at top speed at sea level, the XP-83 had more thrust horsepower applied to it than any other aircraft then known to be flying. The J-33 is also installed in the Consolidated Vultee XP-81 as a tail-booster unit and is part of the power plant of the Martin XP4M-1 patrol bomber.

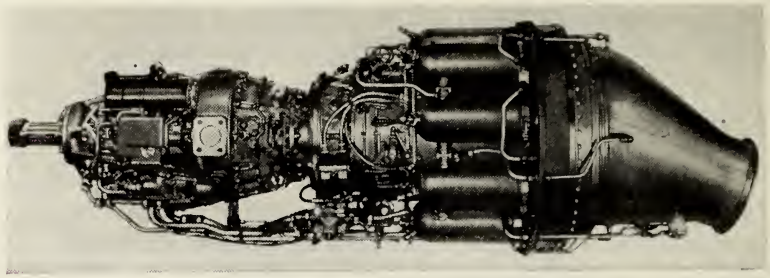
Although the group of engineers at General Electric's Lynn factory has been largely associated with the centrifugal-compressor type of turbojet, based on the Whittle design, other engineers at the Schenectady plant, including A. R. Smith, Alan Howard, G. B. Warren, Dr. C. J. Walker, H. D. Towle, A. J. Nerad, and E. L. Hunsaker, began working in the summer of 1941 on the design and development of an axial-flow gas turbine for propeller drive, the TG-100 (now T-31-GE). This was at the instigation of the NACA gas-turbine committee.

The design and development of both centrifugal- and axial-flow gas-turbine types at Lynn and Schenectady, respectively, have produced an interesting and friendly rivalry within the General Electric engineering family. The work of the several GE plants engaged in these projects was coordinated by J. C. Miller (sales), J. F. Eckel (manufacturing), E. S. Thompson, and W. W. Kuyper. This spirit of friendly rivalry was manifest at the confidential engineering conference held under the auspices of the Army Air Forces and General Electric at Swampscott, Mass., in early June, 1945, where papers and discussions were introduced by both centrifugal and axial proponents. These conferences were extremely valuable and were attended by AAF, Navy, and British technical officers; experts from NACA and other government agencies; and air-frame, "up-and-down" engine, and propeller company engineers. The liaison officer at AAF headquarters for the two GE groups and for other companies who had been given developmental contracts by the AAF was Capt. (later Maj.) Rudolph C. Schulte, who, in October, 1942, was appointed project officer on General Echols' staff for the entire jet-engine program. However, all technical aspects of the program were under Col. Don Keirn of the Power Plant Laboratory, Wright Field, reporting to Brigadier General Carroll, chief of the engineering division, ATSC. Up to the spring

of 1945, when he went with Bell, D. Roy Shoults acted as chief of the engineering liaison among the GE design engineering groups, the AAF, and the various aircraft manufacturers using the GE turbojets.

The T-31-GE unit underwent its initial test-stand run in the spring of 1943—the first test anywhere for this type of power plant. Many design difficulties had to be worked out on the test stand, and the first unit was installed in the Consolidated Vultee XP-81 high-speed fighter in June, 1945.

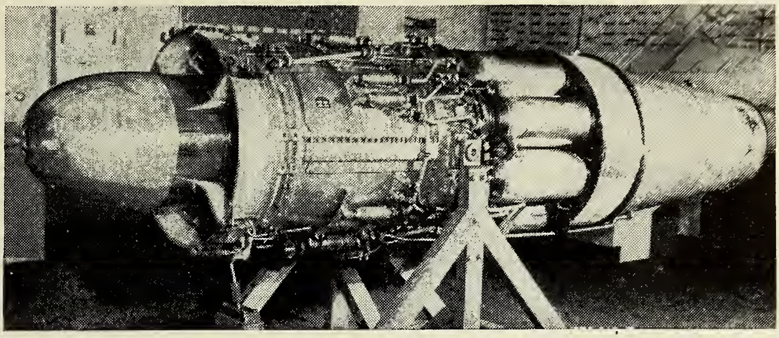
This advanced design, which was test-flown by the AAF at Muroc Lake in January, 1946, and announced by the AAF the next month, incor-



General Electric TG-100 (now T-31-GE) axial-flow gas turbine for propeller drive (propjet) was designed in the summer of 1941 at the suggestion of NACA, Westinghouse being assigned an axial-flow turbojet. The T-31 was bench-tested in the spring of 1943, installed in the XP-81 in June, 1945, and flight-tested in December, 1945. Shaft horsepower is 2,400, with 600 lb of thrust from jet exhaust. (*Courtesy of General Electric Co.*)

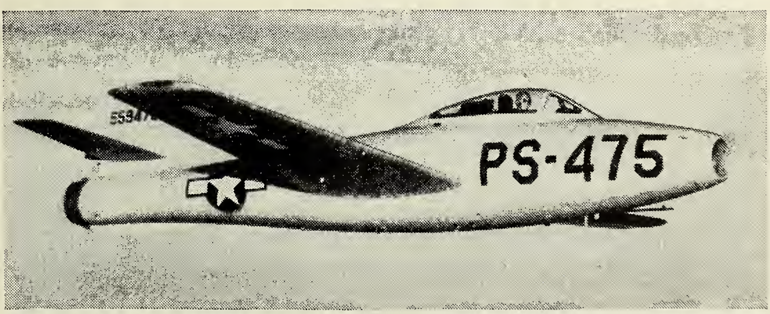
porated a T-31-GE propjet in the nose and a J-33 (I-40) turbojet as a booster unit in the tail. Rated horsepower of the T-31-GE is 2,200, with 600-lb exhaust-jet thrust. The propeller-driving gas turbine in the nose provides fast acceleration, and the jet-propulsion gas turbine in the tail gives sustained high-level speed. The propeller turbine and the jet-propulsion turbine are used together for take-off. For cruising, the nose turbine, driving a four-bladed propeller, is generally used, although the plane can fly on both engines or either one. The two units can produce as much power as the four big engines of the B-29. Top speed of the XP-81 was well above 500 mph; and its range was more than 2,000 mi, to permit its becoming a VLR escort fighter for the Superfortresses. This use of turboprop and turbojet in tandem may indicate a trend toward the use of such power plants in long-range high-speed aircraft of various types. The inspiration for this combination was undoubtedly derived from the Navy's composite-engine carrier fighter, the Ryan FR-1 Fireball, the first aircraft to combine the advantages of a propeller drive (with a

Wright Cyclone radial engine) for fast take-off and acceleration and jet unit for high-speed performance. The advanced Ryan XF2R-1 has the TG-100 turboprop in the nose and the I-16 turbojet in the tail.



General Electric TG-180 (now J-35-GE) through-flow turbojet with 11-stage axial compressor was developed in 1943, test-run in April, 1944, and test-flown in the Douglas twin-jet bomber XB-43 and the Republic jet fighter XP-84 in the late winter of 1945-1946, the first of several bombers and fighters to be powered by this unit. Present thrust is 4,000 lb, but further development is expected.

The development of the General Electric through-flow turbojet with axial compressor was begun in 1943, with the designation "TG-180," since changed by the AAF to "J-35-GE." Whereas the Type I units have a double-inlet centrifugal or radial compressor, the J-35 has an 11-stage



AAF's P-84 jet fighter Republic Thunderjet in flight. Powered by a J-35-GE axial-flow turbojet, design top speed was 600 mph, ceiling 40,000 ft, range 2,000 miles. In October, 1946, the P-84 unofficially broke the record by flying at a speed of 619 mph. (*Courtesy of Republic Aviation Corporation.*)

axial-flow compressor. Although it has eight combustion chambers, the engine as a whole is long and cigar-shaped, having a length of 166 in., maximum diameter of 37.5 in., and weight of 2,400 lb. Static thrust is

General Electric's flying laboratory, the U.S. Army Air Force's B-29 Superfortress, testing in flight a J-35-GE through-flow jet turbine with axial compressor. (*Courtesy of General Electric Co.*)

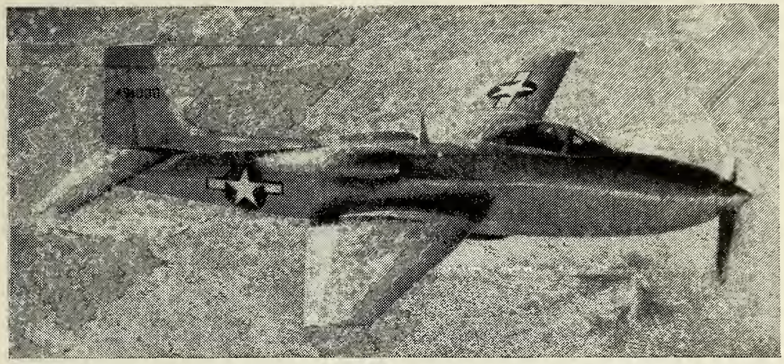
4,000 lb, and the unit is capable of long-term development up to 4,500 or 5,000 lb. A slightly larger, more powerful version is under development. The TG-180 was test-run in April, 1944, and first test-flown in the Republic XP-84 Thunderjet at Muroc Lake in February, 1946. In October of the same year, the XP-84 achieved the official American speed record of 611 mph. The J-35 also is the power plant of several other new AAF fighters in the 550- to 650-mph bracket, including the North American XP-86, the Northrop XP-89, and Republic XP-91 (with rockets).

The first series of AAF jet fighters was designed around the General Electric Type I centrifugal-flow turbojets I-16 (J-31) and I-40 (J-33). These included the Bell P-59A Airacomet, Lockheed P-80A Shooting Star, Consolidated Vultee XP-81 (as tail unit), and Bell twin-jet XP-83. The exception was the Northrop XP-79 prone-pilot flying-wing experimental

The Bell twin-jet XP-83, designed in the autumn of 1943 and test-flown a year later. With more than double the power available for the earlier P-59A and with two J-33 units as against two J-31, the wing area was about the same. Top speed was announced as more than 500 mph. (*Courtesy of Bell Aircraft Corp.*)

fighter, the Flying Ram, powered by the Westinghouse 19B Yankee axial-flow turbojet. This speedy X-job crashed in the autumn of 1945, through no fault of design in either aircraft or power plant.

The second series of AAF jet fighters was powered by the General Electric TG-180 (J-35-GE), as mentioned above (the XP-84 and XP-86). These have all been test-flown. The latest series, now in the works, is to be powered either by the J-35 (XP-89 and XP-91, as above) or by the Westinghouse 24C, a lightweight, compact, axial-flow unit with a present

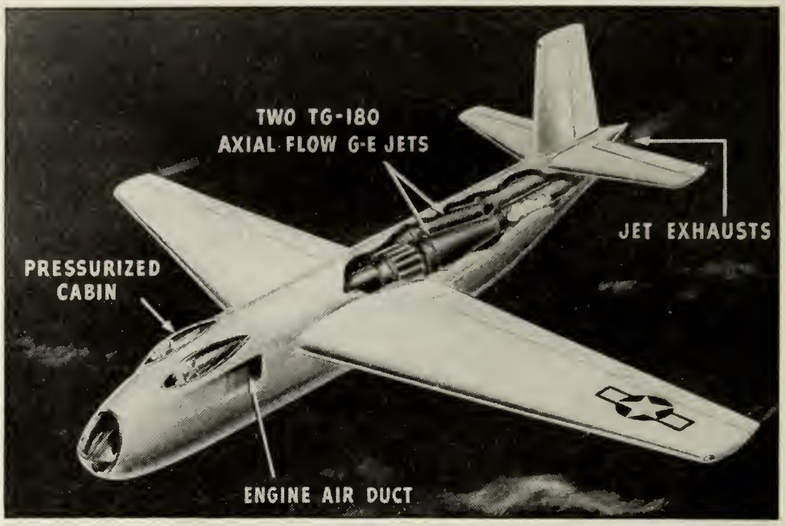


The Consolidated Vultee XP-81 high-speed jet fighter was the world's first tandem-jet aircraft, with the T-31-GE turboprop in the nose and the J-33-GE turbojet as tail booster. With both engines, top speed is well above 500 mph; cruising range, with nose turbine, 2,000 miles. (*Courtesy of Consolidated Vultee Aircraft Corp.*)

thrust of 3,250 lb. These include the McDonnell XP-85 "parasite fighter," to be carried by the B-36 (originally planned to take the smaller Westinghouse 19B); the McDonnell XP-88 all-weather fighter; the Lockheed XP-90; the Curtiss XP-87; and Convair XP-92 (19XB, plus rockets).

Enough is known about these new fighters, and similar Navy developments, to state without fear of contradiction that the aircraft gas turbine has, in the 6 years since the flight of the Whittle-Gloster E28 Pioneer (May, 1941), made the piston-engine fighter obsolete. In this short time, the gas turbine was already looking for new worlds to conquer.

And it didn't have far to look. Even before the middle of 1946, the first of a bumper crop of new AAF jet bombers was in the air, with at least three others due for test flights during the first half of 1947. First of these to fly was the Douglas XB-43, a jet adaptation of the XB-42 Mixmaster, an Allison-powered pusher type which, for a time, held the transcontinental speed record. Other USAF multijet bombers include the North American XB-45 and the Consolidated Vultee XB-46, with four

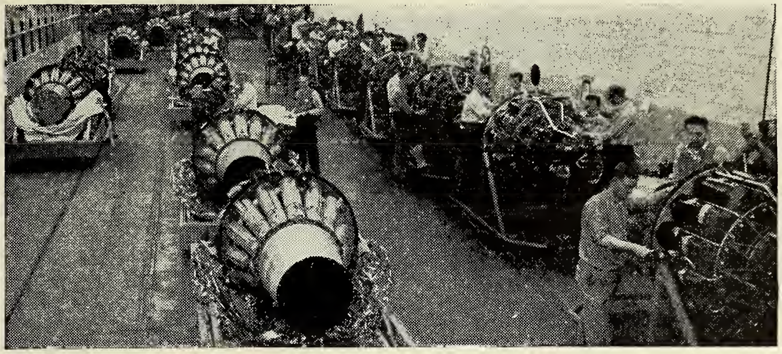


The Douglas XB-43, the world's first jet-propelled bomber, is powered by two General Electric TG-180 (J-35) axial-flow turbojets. The craft was developed from the Douglas XB-42 Mixmaster which was powered by two Allison reciprocating engines driving, via a long extension shaft, a contrarotating propeller mounted aft of the rudder.

Readied for tests in the spring of 1947 was Consolidated Vultee's XB-46. Though classed as a medium bomber, it had a wing span of 113 ft and a length of 105 ft, making it nearly as large as the Boeing B-29 Superfortress. Two General Electric J-35 axial-flow turbojets are housed in each nacelle, giving it the appearance of a twin-engine craft. (*Courtesy of Consolidated Vultee Aircraft Corp.*)

turbojets in two nacelles; the Boeing XB-47 and Martin XB-48 have six jet engines. All these have been test-flown during 1947, which puts the United States out in front in this category. Yet to fly (September, 1947) are the Martin XB-51 and Boeing XB-52 high-speed super bombers and two prototypes of the Northrop YB-49 eight-jet flying wing. All these bombers are powered by Allison J-35 axial-flow turbojets, in some cases to be replaced by more powerful units when they become available. The Northrop YB-49 is a big flying wing, to be fitted with eight J-35 units.

When transport versions of some of these bombers become available, possibly in the early 1950's, the array of air-transport speed records hung up during the first few weeks of 1946 will be far surpassed.



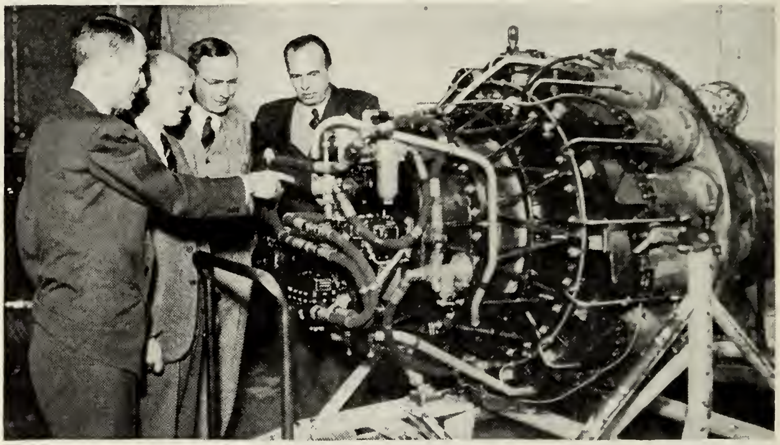
The world's biggest production line of turbojet engines is at the Allison Division of General Motors, Indianapolis, where GE-developed, Allison-improved J-33 units are produced for the P-80A and Convair P-81 (tail booster).

The original AAF team for the development of fighters to be powered by Whittle-type turbojets was General Electric, Bell and Lockheed, working with Wright Field. To increase production of the Type I units, once the I-40 had been successfully flight-tested in the P-80A (June, 1944), the Allison division of General Motors was brought into the picture. The AAF negotiated contracts for a substantial number of GE-designed I-16 and I-40 jet engines; but before volume production could get under way, the I-16 contract was canceled as Lockheed Shooting Stars began to replace Bell Airacomets in the 412th Fighter Groups jet-training program in California.

Allison engineers, including J. C. Fetters and T. S. McCrae, worked closely with General Electric in solving problems associated with the J-33 engine. A list of all the known difficulties was drawn up, and responsibilities were divided between the two organizations. At the same time, basic engine design was being interpreted into shop drawings. As fast as piece drawings were completed, they were rushed into the Allison

shop or to the many suppliers set up for important parts production. The urgency of the production situation coupled with the need for important improvements in detailed parts necessitated the closest liaison among the two engine manufacturers, suppliers, Lockheed, and Wright Field.

Principal Allison contributions to the engineering program involved improvements in barometic controls, governor, fuel nozzles, and accessory



Aircraft gas-turbine engine team at Allison Division, General Motors, with J-33 turbojet. *Left to right:* T. S. McCrae, Assistant Director of Engineering; J. C. Fetters, Chief Turbine Engineer; C. J. McDowall, Chief Development Engineer; Fred Luker, Chief Production Engineer.

housing. But even more particularly, Allison was able to make extremely valuable contributions to the most vital part of the jet unit—the turbine wheel and turbine-wheel buckets. As a result of these and many other detail changes, the reliability and durability of jet engines were greatly increased, and the performance of the P-80 definitely improved, from a top speed of 550 to more than 580 mph.

In late spring of 1946, Allison completed development of a number of additional detail improvements to the J-33; and in May, this new version, the J-33-17 (Navy I-40-4), went into production; static thrust is 3,850 lb. During the same month, this improved jet engine successfully completed a 100-hr type test. Further improvements in the J-33-17 and -21 were confirmed in a 150-hr type test in early 1947. A more radically improved and lighter weight version known as Model 400 (Air Force J-33-23) with thrust of 4,600 lb, powered the record-breaking P-80R (623.8 mph at Muroc Lake, June 19, 1947). A redesigned compressor,

permitting a greater air capacity (as in the Nene), will result in yet higher thrust for still later J-33 models. In addition, production and development of the J-35 axial flow unit (GE-designed TG-180) have been taken over, with some 1,200 units on order. First Allison J-35's were produced early in 1947. These two projects give Allison the benefit of experience on both centrifugal type and axial-flow compressor type units to exploit in development work on more powerful turbojet and turboprop engines for which development contracts have been accepted. This puts Allison squarely in the jet and turbine field as a prime development as well as major production source. D. Gerdan is project engineer on the J-35.

All development work and most of the production up to mid-1945 of the I-16 and I-40 were at General Electric. Production and development of the I-40 went to Allison in 1946. Development and production of the TG-180 were at General Electric up to the end of 1946, when Allison took over production and production engineering of the J-35, including a considerable amount of production facilities which had been laid out at GM's Chevrolet-Tonawanda plant, where a few dozen units were completed. General Electric continued some TG-180 production into 1947, supplying the jet engines for the first production P-84's. Production and development of the TG-100 (T-31-GE) turboprop continued at General Electric until the project was dropped.

In addition to this, however, a substantial expansion program, extending through 1947-1948, of the aircraft gas-turbine division (Lynn), one of the company's largest, is now under way. This includes a badly needed laboratory with test facilities for new and far more powerful turbojets, turboprops, and their components than any now in operation and also increased production facilities. Instead of the handful of engineers, draftsmen, and manufacturing men of the old supercharger department which designed and built the original I-A jet unit in 1941-1942, there are now more than 100 gas-turbine design engineers alone.

Besides this pioneer work in the jet field done by General Electric and Allison for the AAF, other highly important research and development programs were begun during the war. Wright Aeronautical Corp. has a powerful turboprop (XT-35) under development to be test-flown during 1947 in the nose of a B-17.

Under the direction of Arthur Nutt, director of aircraft engineering, Packard Motor Company began an experimental turbojet program early in 1944, with 150 specialists assigned to the project. There are now over 500, located at the modern developmental facilities in Toledo, with testing facilities at Willow Run. The main project to date has been a lightweight turbojet engine of ingenious design and of an expendable

type, planned to be used primarily for pilotless aircraft. Packard has its own designs for more powerful jet units on the drawing board or under development.

Lockheed began work in 1943 on an ingenious turbojet designated "L-1000" and in October, 1945, turned over the manufacturing rights, together with the services of its entire gas-turbine engineering staff (headed by Nathan C. Price) to Menasco Mfg. Co., which had worked closely with Lockheed on the development of the unit, now designated "XJ-37." The larger L-4000 has run on the bench and will be further tested during 1947.

The Northrop-Hendy Turbodyne (XT-37), a multistage, axial-flow turbine-propeller unit, has been under development since 1941 and was announced at the National Aircraft Show, Cleveland, in November, 1946. A more powerful unit is in the design stage.

Other companies with AAF or Navy contracts for design studies or development projects include: Wright Aeronautical; Pratt & Whitney; Fredric Flader, Inc.; Continental Motors; and de Laval Steam Turbine Company. Wright Field has announced that some of the turboprops under development by the AAF will be in the 5,000- to 10,000-shp bracket and turbojets up to 8,000 lb of thrust. Their successful development will mean only one thing—new horizons for AAF bomber and transport planes as well as fighters.

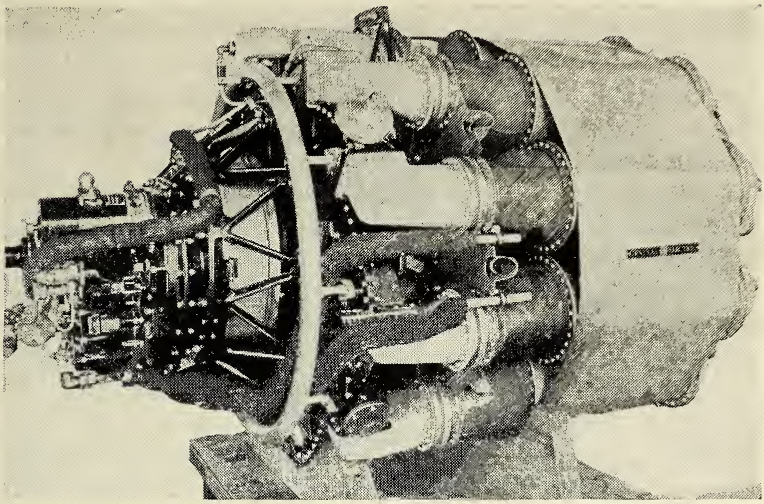
THE GENERAL ELECTRIC I-16 TURBOJET [1]

As Allied successes progressed favorably in World War II, more and more information was made public on the advancement of jet-propulsion research and development by both the AAF and BuAer (Navy Bureau of Aeronautics). Yet the releases divulged very little about the most vital unit of the development—the jet-propulsion engine.

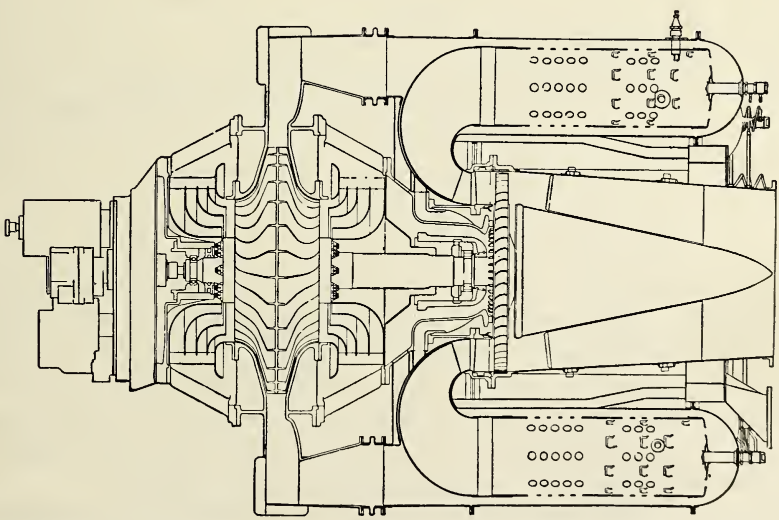
The General Electric Type I-16 jet engine and the Bell P-59A Airacomet were pioneer developments in a new and important era in American aviation. The first American jet-propulsion engine ("turbojet unit," as it is now known) was built by GE at Lynn, Mass. Behind this prosaic statement of fact is an outstanding record of achievement by industry and the military services.

Basic conventional engines used in our combat aircraft had substantially reached the limits of power of which they were capable without major changes and redesign. Such major changes and redesign were, of

[1] Based on a design analysis by Maj. Rudolph C. Schulte, which appeared in *Aviation*, January, 1946.



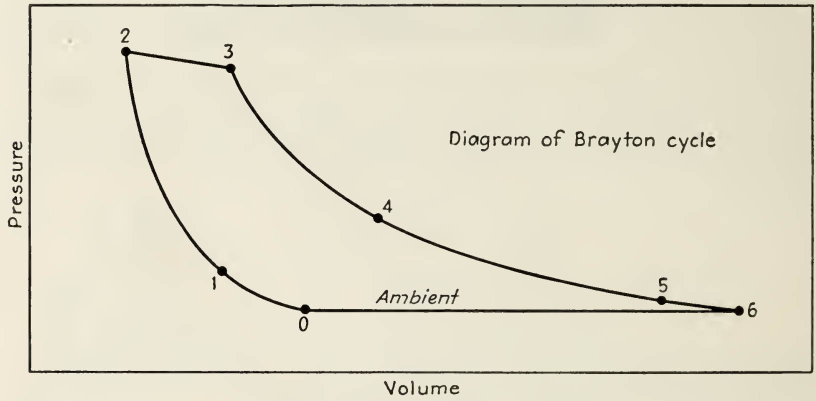
General Electric I-16 (J-31-GE), designed after the successful flight tests of the I-A turbojet in the Bell P-59A, was test-run in April, 1943. Static sea-level thrust at 16,500 rpm was 1,650 lb against a weight of 825 lb. It is the power plant of the Bell Airacomet and the tail-booster unit in the Ryan Fireball.



Schematic view of the I-16 turbojet engine, showing successive conditions of ram air, compressed air, combustion, and exhaust.

course, not feasible in the short time available while the war was being fought. It became apparent that still more speed was essential, and this could not easily be obtained with the piston engines available. Jet propulsion appeared to be an obvious solution—particularly since theoretical studies indicated that certain forms of jet propulsion resulted in an increase of thrust as the value of speed was increased.

While visiting England early in 1941, General Arnold had an opportunity to examine, firsthand, the results of British activities in the field of jet propulsion, particularly the Whittle turbojet engine which was successfully test-flown in a Gloster experimental fighter in May. Arrangements were completed to produce Whittle-type jet engines at General Electric (Lynn) early in September, 1941. (For complete details on these important developments, see pages 102 to 105.)



Pressure-volume diagram of Brayton cycle, I-16 turbojet.

The first test experience with the Whittle engine was obtained by GE in November, 1941, resulting in a static sea-level (sl) thrust of 1,200 lb, and data obtained proved invaluable in building the first GE unit—the Type I-A turbojet. In March, 1942, just 28 weeks after the project was begun, this first unit was running on the test stand; and although it was the same in principle as the Whittle unit, many design changes had been incorporated to increase thrust and efficiency.

Meanwhile, Bell personnel were designing and building a twin-engine jet-fighter plane, the XP-59A; and on Oct. 1, 1942, this craft, powered by two GE Type I-A turbojet engines, made its first flight at Muroc test base in the desert area near the West Coast.

The flight symbolized an important achievement in aviation progress

in this country; for within the short time of 1 year 3 weeks, the complex problems involved in the design and construction of the jet plane had been overcome.

Early in the GE program, because of the need for design changes in the Whittle engine, modifications in the area of the diffuser throat, turbine nozzle, and exhaust nozzle were found necessary to reach the full rated speed without pulsation and were incorporated in the Type I-A. When tested in May, 1942, this design gave about 1,400 lb static sea-level thrust at 16,500 rpm with a tail-pipe temperature of 1200°F and sfc (specific fuel consumption—pounds of fuel per pound of thrust per hour) of 1.3.

Success of the Type I-A engine in flight and static tests spurred AAF personnel and GE engineers and metallurgists to increased efforts. Great strides were made in the development of high-temperature alloys, controls, and accessories; in methods of bearing cooling; in combustion research, and in redesign for production. Thrust output was increased and sfc lowered.

By April, 1943, an improved turbojet engine, the Type I-16, was completed and running on the test stand. This power unit, rated at 1,650 lb static sl thrust at 16,500 rpm, with a tail-pipe temperature of 1180°F and sfc of 1.18, became the first satisfactory American model to be released for quantity production.

The I-16 (Army designation, "J-31") is substantially a complete power package, weighing only 825 lb with all attached accessories and having an estimated installed weight of 1,054 lb. Dimensions and other mechanical data are given in the following table:

Table III. *Type* I-16 *Turbojet Data*

Impeller	20.69 in.
Diffuser throat area	30.6 sq in.
Turbine-nozzle area	54 sq in.
Turbine-pitch diameter	14.2 in.
Turbine-nozzle and blade height	2.76 in.
Exhaust-pipe diameter	14.4 in.
Jet-nozzle diameter	12.4 in.
Maximum over-all diameter	41.5 in.
Over-all length	70 in.
Average weight	825 lb
Center of gravity (aft of trunnion)	8.5 in.

Operational Details

The rotor (basic assembly element and only moving part) consists of a centrifugal air compressor connected to a single-stage turbine wheel.

Atmospheric air enters at the front of the engine through circumferential guide vanes located at front and back of a double-sided impeller. These inlets are covered with a screen to keep large particles of dirt or other foreign matter from entering the air intake. Air is scooped up by the impeller, compressed to approximately 3.75 atm, and discharged at a high velocity into 10 equally spaced diffuser channels in the compressor casing, which distribute it evenly through a series of air adapters leading into the 10 combustion chambers. When the compressed air reaches a combustion chamber, it flows between the outer casing and inner liner and then through a series of holes to the inside of the liner, where it is mixed with fuel introduced by the fuel nozzle.

Burning of the fuel occurs all the way down the liner and is complete before the gas enters the elbow leading to the turbine. During starting, the fuel is ignited by two spark plugs—one each located on the outside of two combustion chambers. The resulting gas expands instantaneously and is directed through the curved blades of the turbine-nozzle diaphragm against the blades of the turbine wheel, causing the latter to rotate and, in turn, drive the impeller via the shaft. A substantial amount of the energy in the gas is utilized by the turbine to rotate the compressor. The energy remaining in the gas is used to produce a high-velocity jet through the exhaust nozzle, and thrust is developed through reaction to this discharge.

The unit operates on the Brayton cycle, shown in the P-V chart on page 124. The compression curve is designated by 0-1-2, and heat added at "constant pressure" is indicated by 2-3. Pressure loss in combustion chambers is also indicated as droop between 2 and 3, and curve 3-4-5-6 is the expansion line to ambient pressure. Conditions represented are as follows: Point 0 represents the condition of ambient air at rest; point 1, condition of this air at the inlet to the impeller after it has entered the ram inlet and has been diffused, with some efficiency, to reduce its velocity substantially to zero relative to the plane; point 2, air at the discharge of the compressor; point 3, gas at the inlet to the turbine; point 4, gas after expansion through the turbine; and point 5, gas at the nozzle throat. Points 5 and 6 tend to combine at 6 as velocities at the final jet nozzle reduce from supersonic to sonic, and they are one and the same point at all subsonic-exit velocity conditions.

Major Components

SINGLE-STAGE TURBINE. A nozzle diaphragm, turbine wheel, and shaft make up the single-stage impulse turbine. The diaphragm—constructed

of high-grade heat-resisting steel—has a series of curved blades designed to direct the gas against the buckets of the wheel. The low-alloy-steel shaft is flash-welded to the Timken-steel wheel, and the assembly is heat-treated to relieve strains. Securely dovetailed into the outer rim of the wheel is a continuous circle of curved blades (buckets) forged from a nickel-molybdenum alloy called "Hastelloy B."

Centrifugal Air Compressor. A double-sided, multiple-vaned wheel (impeller) enclosed in a casing, together with a diffuser, comprises the centrifugal air compressor. The impeller is a heat-treated aluminum forging capable of withstanding the high speed at which it must revolve. The curves of its vanes are designed to admit the high-velocity fluid without shock and to decrease the fluid volume by compression with greatest efficiency. The magnesium-alloy compressor casing consists of front and rear halves. The curved, smoothly machined undersurface of the front casing fits over the forward side of the impeller, and the rear compressor casing is cast with 10 identical channels radiating outwardly. These channels constitute the diffuser, and through them the air is efficiently distributed into the elbows attached to the combustion chambers.

Rotor Assembly. This component—turbine wheel and impeller at opposite ends of a composite shaft mounted on antifriction bearings—is a finely balanced precision assembly constituting the heart of the engine. The wheel shaft is machined with a ball-bearing journal, a shoulder for an oil slinger, and a series of splines. After the slinger and bearing are slid down the shaft, a rear shaft—correspondingly splined—is fitted over the entire wheel shaft with a shrink fit. This composite shaft is then secured with a spring collar, shims, and a shaft lock nut. The impeller is assembled to the end of the rear shaft with eight studs on one side inserted into drilled holes on the flange of the rear shaft, and eight on the other side inserted into drilled holes in the flange of the front shaft. Assembled to the front end of the front shaft are an oil slinger and a ball bearing which are secured in place with a lock washer and nut.

After the rotor has been assembled, it is given a runout check at four places to ensure proper alignment. When it is in true alignment, it is dynamically balanced.

Combustion Chambers. Each of the 10 counterflow combustion chambers consists of an outer casing of stabilized 18-8 stainless steel and an inner removable liner of Inconel. Outer chambers are linked by short connecting pipes into which liner interconnectors of the same metal are inserted to link the liners. Each combustion chamber is sealed at the end by a domed cover containing a burner nozzle for introduction of

fuel. A curved elbow leads from each combustion chamber to the turbine-nozzle diaphragm.

Exhaust Cone. This installation is a tapered, cylinder-shaped outlet for the exhaust gas, and within it is a closed cone around which the gas is ejected in a gradually expanding jet form. All the turbulence of the expanding gas is converted into direct thrust as it is discharged. Bolted to the unit at the rear of the turbine wheel, the exhaust cone extends out through the space in the center of the combustion chambers. The inner cone is supported within the outer cone by four radial rods covered with thin, streamlined, stainless-steel vanes. Material of the exhaust cone is stainless-steel sheet flanged with steel forgings at both ends; and to keep as much of the heat energy as possible within the cone, it is covered with four layers of aluminum foil, each separated by a layer of bronze screening.

Power-plant Accessories. Accessories are located at the front of the unit and consist of the starter, starting fuel pump, main fuel pump, governor, lubricating and scavenger pump, tachometer generator, and generator.

Lubrication. The engine is lubricated by a relatively simple dry-sump system. Mounted in the airplane is a 2-gal (1.66 Imperial) oil tank with a direct connection at the bottom to the lubricating and scavenger pump on the accessory-drive assembly, which forces oil to the various parts of the machine. From the pump, the oil passes through a filter that removes sediment and foreign matter and then proceeds through a relief valve where the pressure is properly limited for distribution. One line carries the oil to the accessory gear drive and casing through the ball-support housing, and a second line delivers it to the front and rear bearings on the rotor shaft. If the pump should build up too much pressure, the lubricating relief valve, which is set at 9 to 11 psi, will open and by-pass oil directly back into the inlet side of the lubricating and scavenger pump.

Each bearing is supplied with air, which is bled from the compressor casing and directed through an air filter, where it is cleansed and then delivered to each bearing case. The air stream atomizes the oil to the rear bearing, causing an efficient distribution by spray lubrication. Air is introduced into the front bearing through an opening in a double oil seal. On one side, it is forced through the seal to the bearing, where it mixes with the oil to give complete distribution; on the other, it escapes to the atmosphere. The mechanical oil seal is thus rendered doubly effective.

Fuel System. This is a mechanical pressure system activated by a main engine-drive fuel pump aided by an external motor-driven booster

pump that provides adequate flow of fuel to the main pump at high altitudes, compensating for the loss of atmospheric head. Operation of the system at starting differs slightly from normal running operation, in that the main fuel-pump discharge is by-passed by a check-and-relief valve to the starting fuel pump. By pressing the starter button, the starting fuel pump—geared to the starting motor—is set in operation and continues to function until the main fuel pump has reached a speed sufficient to establish a fuel pressure ensuring self-acceleration of the unit. At this point, the check-and-relief valve isolates the starting fuel-pump discharge, allowing flow directly from the main fuel pump. Fuel flows from the main fuel tank, passes through the booster pump and filter, and from there goes to the inlet connection on the main fuel pump.

During both starting and normal running operation, the fuel flows from the main fuel pump to a barometric valve, which is so constructed that, as altitude changes, fuel is by-passed back to the fuel tank to maintain approximately constant speed for a given throttle setting. From the barometric valve, fuel passes to the throttle valve, which is controlled by the throttle-valve quadrant in the pilot's compartment, and then to the governor, connected through a train of gears to the engine rotor. The governor also functions to control the maximum rotor speed by restricting the fuel flow, causing the barometric valve to pass more fuel back to the tank. From the governor, fuel is passed on to the stopcock, then to the drip valve and into the fuel manifold and burners. To stop the flow of fuel, the pilot closes the stopcock through the medium of a quadrant, thus cutting the supply to the burner manifold and stopping the unit.

Various types of fuel can be burned—kerosene, low- or high-octane gasoline, or furnace oil—but change from one fuel to another requires some modification in the fuel system. With kerosene, fuel pressure is 250 psi at rated speed.

Electrical System. The electrical system consists of a generator, reverse-current relay, storage battery, control switches, undercurrent relay, starting motor, two ignition coils, and two spark plugs. The generator—mounted on the accessory casing at the front of the unit and geared to run at 3,800 to 6,000 rpm—is a four-pole, compensated, commutating type, rated at 28.5 v and 50 amp, and is cooled by ram air through an air-blast cover. The storage battery is a standard type with capacity of 24 v and 17 amp-hr. The ignition system is used only while starting the unit. As soon as burning of the fuel becomes complete, the starter and undercurrent relay automatically discontinue the electrical operation.

The I-16 turbojet incorporates a three-point support with two main trunnions in the horizontal plane and a front support in the vertical plane. Principal loads are carried by the two main trunnions. To minimize bending stresses transmitted from the airplane structure, only one of the trunnions is mounted to the airplane by a ball joint, the other being fastened by a slip joint. Front support is fastened by a ball-and-socket arrangement. Gyroscopic forces arising from pitching, sharp turns, and spin maneuvers are considerable and were given due consideration in designing the three mounting supports. However, amplitude of vibration in the I-16 is so small that no vibration dampening is required in the mounting.

Compared to the conventional type of aircraft power plant, vibration produced by the turbojet unit is practically negligible. Smoothness of operation resulting from absence of vibration is one of the advantages and desirable characteristics of the gas turbine. The I-16 engine operates so smoothly that it was necessary to install a vibrator on the instrument panel to make the conventional instruments function properly. Normal vibration of the conventional airplane and engine combination is sufficient to cope with static friction in the instrument bearings, whereas the turbojet plane lacked this characteristic. Aside from smooth operation, the jet engine is much quieter. This trait, coupled with absence of vibration, lessens pilot fatigue to a marked degree.

Ram efficiency affects operation of the I-16 much more than it does the operation of a conventional engine; hence great care has been given to the design of inlet ducting to ensure a ram efficiency of at least 85 per cent or better. Air-flow requirement of this unit at rated rpm is approximately 420 cfs—varying with altitude and air speed.

Installation in the P-59A has been very reliable and has demonstrated an excellent safety record. Experience has shown that the turbojet presents no greater fire hazard than does the conventional engine. Major potential fire hazards are fuel and exhaust systems, the lubrication system being considered only a minor hazard. Hot portions of the engine are adequately isolated from the airplane structure by insulating material. Potential hazard in the fuel system is being reduced by improvements in piping and fittings and will be further minimized by a new fuel system being developed with a minimum number of separate accessories and connecting lines.

Performance Considerations

In general, jet propulsion is based on the reaction principle: For every action there is an equal and opposite reaction. However, this does not

define the operation of the I-16 with sufficient accuracy, since it can be said that any propulsion in a fluid medium is based on imparting momentum to the fluid in such manner that the reaction of the imparted momentum furnishes the propulsive force. Rotation of a conventional propeller increases the momentum of the fluid passing through the propeller disk, and thus the propeller thrust can be considered as the reaction of the increase of momentum.

Propulsion of a rowboat, swimmer, or bird is also based on the principle of reaction. And to differentiate between jet and other methods of propulsion, it should be noted that jet propulsion exists when matter is ejected from the propelled body to create momentum. In the case of the I-16 turbojet, this matter is taken from the surrounding medium—the air—which is taken in at the front, heated by compression and the addition of fuel, and then ejected from the rear at high velocity. As previously stated, thrust is developed through the high-velocity discharge.

The question of how fast this high-velocity discharge is can be answered as follows: In a continuous-flow process, where a fluid such as air is accelerated from an approach velocity V_p to a final velocity V_j, a continuous-reaction thrust F is obtained:

$$F = \frac{(W_a + W_f)V_i}{g} - \frac{W_a V_p}{g}$$

From a typical test-data analysis of a I-16 unit operating at rated rpm of 16,500 and corrected to standard conditions of temperature and pressure (see Table III, page 133):

F = 1,670 lb static sea-level thrust
W_a = 32.9 lb/sec air flow
W_f = 0.54 lb/sec fuel flow
g = acceleration due to gravity, 32.2 ft/sec ^{2}

Assuming the unit to be at sea level and at a standstill, V_p would be zero. Therefore, to solve for the jet-nozzle discharge velocity V_j, we have

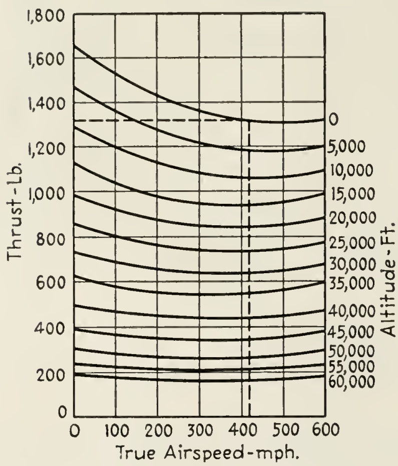
$$V_i = \frac{gF}{W_a + W_f} = \frac{32.2 \times 1.670}{32.9 + 0.54}$$

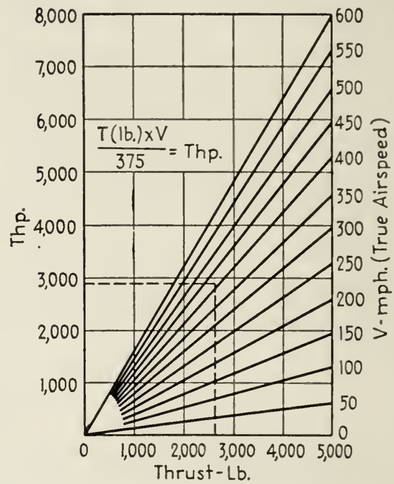
$$= \frac{53{,}774}{33.44} = 1{,}610 \text{ fps}$$

This high-velocity discharge flows from a jet nozzle of 12.4 in. in diameter.

Since the turbojet engine is rated in pounds of thrust, instead of horsepower, it may be asked how the output of a turbojet can be compared with that of a conventional engine rated in bhp. This can easily be done by introducing the element of speed. Suppose we are interested in determining the approximate total bhp being delivered by the two I-16 turbojets in a P-59A flying at a speed of 420 mph at sea level.

First, we obtain from the accompanying thrust chart the thrust obtainable from each engine at rated rpm at sea level at 420 mph. From





the intersecting dash lines, we obtain a thrust figure of 1,320 lb; and total thrust for the twin-engine P-59A is twice that value, or 2,640 lb. From the chart of thrust horsepower (thp) vs. thrust, we find that at 420 mph and a thrust of 2,640 lb, the turbojets are supplying 2,900 thp. This is an approximate figure but sufficiently accurate for all practical purposes. To obtain bhp, thp is divided by propeller efficiency. At the speed in question, a propeller efficiency of approximately 80 per cent would be achieved. Hence, the equivalent bhp output of the two turbojets under the conditions stated would be 2,900/80, or 3,620.

By reference to these two charts, it can be seen that the thrust available is fairly constant throughout the speed range, especially at altitude. This means that fuel is burned at practically a constant rate. Hence, to take full advantage of this available thrust, it is most important that the airplane in which the turbojet is installed should be as clean as possible aerodynamically.

Metallurgical Factors

To the metallurgist must go a large measure of the credit for the success of the turbojet unit as we know it today. One means of increasing the efficiency of this type of power plant will be by raising the temperature of the gas at the turbine inlet. This increase in temperature can be achieved only if improved temperature-resistant materials are made available. The importance of advancements that have already been made cannot be too strongly emphasized. If the metallurgist had been unable to

Table IV. *Turbojet Average Performance at* 16,500 *Rpm with Standard Inlet Conditions of* 14.7 *Psi* 59°F *and* 0 *Ram*

Thrust	1,670 lb
Fuel flow	54 lb per sec
Specific fuel consumption	1.18 lb/lb of T/hr
Exhaust temperature	1180°F
Compression ratio	3.75
Compressor-discharge temperature	380°F
Combustion-pressure drop	1.92 psi
Turbine-inlet temperature	1485°F
Air flow	32.9 lb per sec

provide materials suitable to withstand the high temperatures and tremendous centrifugal stresses anticipated by the design engineers for this new type of plant, the I-16 and other improved models would not have materialized.

Turbine wheels are massive and rotate at terrific speed at high temperature. This presents many problems, the most difficult being to develop a material with high yield strength for the center of the wheel and high rupture strength at the rim. Materials chosen for the first turbine wheels (disks) were chromium-nickel alloys such as 17W and Alpha CB. These were replaced by the Timken wheel now used on production units.

Selection of alloys for turbine buckets is equally critical and is based on rupture strength at 1500°F and up. As rupture strength increases, forgeability usually decreases. And as forging difficulties increased, more and more attention was given to the development of cast buckets. Several types of heat-resistant alloy, which have proved so successful in the turbosuperchargers used in our high-altitude planes, were tried as turbine-bucket material for the I-A and I-16 turbojets. Among these are Vitallium, a cobalt-chrome-molybdenum alloy; 19-9-DL, a chrome-nickel alloy having high rupture strength; and Hastelloy B, high in nickel and molybdenum content.

A large amount of development testing has been done with both forged and cast buckets, and these were attached to a turbine wheel by welding or by mechanical means, such as the dovetail or Christmas-tree attachment used on the British unit. For production-engine bucket material, Hastelloy B was chosen as the best available, and buckets made from it are forged and attached to the turbine wheel by the Christmas-tree method.

Turbine-nozzle blades are made of either molybdenum or columbium stabilized 18-8 stainless steel. These alloys have good welding characteristics and are easily forged. Blades are fastened into the diaphragm by insertion between inner and outer ring, then fillet-welded in place.

High-temperature sheet-metal parts—expansion bellows, outer casings, inner liners and interconnectors of the combustion chambers, elbows, tail cone, and other parts—are made of heat-resistant material ranging from 0.015 to 0.030. Inner liners and interconnectors are usually made of Inconel, whereas other sheet-metal parts are made of stabilized 18-8 stainless steel.

The turbojet operates best at a point near its maximum output condition. Operation of its compressor at reduced speeds would mean an alarming decrease in output coupled with an increase in specific fuel consumption. For efficient operation, the turbojet must be associated with high speeds—speeds usually beyond that obtainable with the conventional engine-and-propeller combination. Or, to express it another way, for the best results, an airplane equipped with turbojet engines must fly within 10 or 15 per cent of its maximum speed. The conventional engine, on the other hand, behaves differently, since, to obtain the most economical operation in miles per gallon of fuel consumed, engine output can be reduced to 50 or even 40 per cent of its rated power. Continuous operation of the conventional engine at a point near its rated output means abnormally high specific-fuel consumption and short engine life.

For efficient operation, the turbojet must also be associated with high altitude, since the lower temperature at altitude increases the compression ratio of the compressor (as much as 25 per cent at 40,000 ft) and decreases specific fuel consumption of the engine. As altitude is increased, airplane drag is decreased; and this, in turn, results in a substantial decrease in power required for the same forward speed. Obviously, all types of aircraft and missiles, no matter how propelled, benefit from decreasing air density to the extent that air resistance or drag decreases. Add these factors together, and it will be evident that airplane endurance can be greatly increased for the same fuel consumption when flying at high altitude and at no sacrifice in speed.

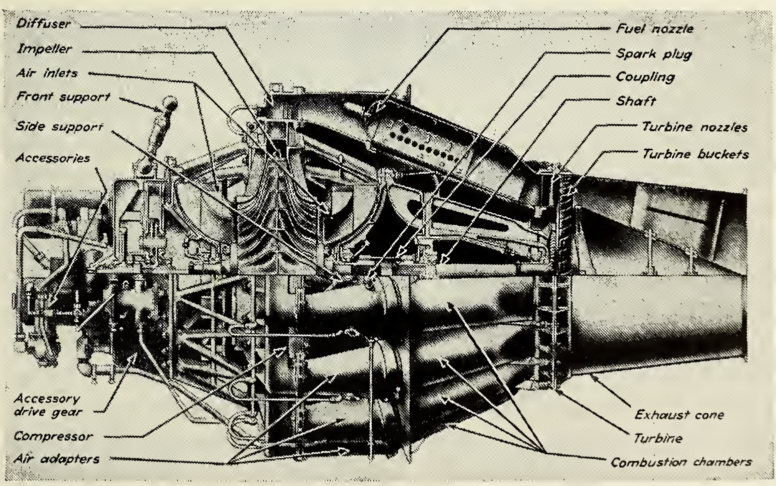
For example, when flying at maximum speed at sea level, the P-59A has an endurance of approximately 35 min with normal fuel load. However, when flying at that same speed at 40,000 ft with the same amount of fuel available at the start of the flight, its endurance, including climb to altitude, is increased to 100 min. This means that in a jet-propelled plane, such as the P-59A, one can fly almost three times as far if immediately upon take-off a climb is made to a suitable altitude.

The turbojet will supplement and eventually replace the conventional engine—first in fighter craft; then in superspeed bombers; and finally in transport, both military and civil. At the present state of development, however, it is difficult to foresee any application of jet propulsion to private flying in the immediate future.

THE GENERAL ELECTRIC I-40 TURBOJET [2]

Early in 1943, at the request of the AAF, the General Electric Co. started the study of a jet-propulsion gas turbine to have considerably higher rating than any jet-propulsion gas turbine then in existence.

At the request of Col. D. J. Keirn, ATSC, and the company's engineering division development committee, this original design study was aimed to create a unit having 3,000 lb static thrust. The value was later revised



Cutaway view of the GE type I-40 turbojet engine (J-33-GE), which was bench-tested to produce 4,200 lb of thrust at 11,500 rpm within 8 months of its design. Weight, 1,820 lb. (*Courtesy of Aviation.*)

[2] Based on a design analysis by Dale D. Streid, which appeared in *Aviation*, January, 1946.

to 3,500 lb, and still later it was decided that a gas turbine with 4,000-lb static thrust at sea-level standard conditions would be the objective. The project unit became known as the "Type I-40 (military version J-33) jet-propulsion gas turbine (turbojet)"; and in June, 1943, it was decided to proceed with the development.

Three months were spent completing the design and making drawings for the manufacture of the first development unit. As soon as the drawing for a part was completed, production of the unit was begun. And in January, 1944, the first I-40 power plant was completed, delivered to test, and run up to 8,000 rpm. In subsequent tests, the turbine was run at various speeds up to 8,700 rpm—a limit observed because the buckets had an unfavorable tilt and were considered unsatisfactory for operation at higher speeds.

In a month, after a new turbine wheel had been installed, the following performance data—which have been corrected to standard conditions of 14.7 psi and 59°F at the compressor inlet—were obtained:

Table V

Speed	11,500 rpm
Thrust	4,200 lb
Fuel flow	5,070 lb/hr
Exhaust temperature	1300°F
Jet diameter	18.2 in.

In so far as was known at the time, 4,200 lb was the highest thrust ever obtained with a jet-propulsion gas turbine. Performance data were generally very gratifying, but the exhaust temperature was much higher than desired; and, accordingly, the jet diameter had to be increased to 19 in. to keep the exhaust temperature below the desired limit of 1200°F.

Additional I-40 development units were soon completed, making a total of four. The first three were used for performance and endurance tests and never for flight. The fourth was shipped to Lockheed at Burbank, Calif., and was there installed in the first XP-80A Shooting Star.

First trial of the Lockheed XP-80A—made at Muroc, Calif., on June 10, 1944, less than a year after the start of the development project—was a flight of about 30 min to an altitude of 10,000 ft, and operation of the I-40 jet engine was considered very satisfactory.

Since the first flight of the Shooting Star, further development of the I-40 has proceeded rapidly. As would be expected with a power plant of such new size and design, many problems arose following factory testing and flight operation. Among those difficulties requiring considerable attention were: exhaust-cone buckling, sticking of automatic controls, carbon

formation, and fuel-pump wear. These details were brought under control, and manufacture of the I-40 gas turbine proceeded fundamentally in accordance with the same design laid down during the summer of 1943.

I-40 *Operation Principles*

Air enters the compressor of the jet engine through circumferential inlets on the front and back of a double-sided impeller, the inlets being screened to prevent particles of dirt or stone from entering the air intake. The air is turned into the annulus of the impeller by guide vanes and a single splitter vane. Design of the inlet does not impart any preswirl to the air as it enters the impeller. The impeller is a solid aluminum forging with milled blades having inlet sections bent to match incoming air flow. Discharge from the impeller enters 14 equally spaced diffuser passages; and at the end of each is a Wirt-type elbow containing four vanes, which turn the air 90 deg into the compressor discharge.

Air from the compressor outlets is conducted to the combustion chambers by cast air adapters, which carry the fuel nozzles, domes (end caps) of the combustion chamber, and spark plugs.

The 14 combustion chambers are of the through-flow type, with air entering from the compressor end and leaving at the turbine end in the same direction. Combustion is controlled by holes in the liners, and outer tubes are cooled by compressor discharge air before it enters the liners. A thin film of air travels the full length of the liners to provide cooling at the liner ends at the turbine inlet. During starting, ignition is obtained from two spark plugs mounted in diametrically opposite air adapters, and ignition for the other combustion chambers is obtained by utilizing cross-ignition tubes.

A turbine-nozzle ring—containing 48 blades—directs the hot gas on to the turbine wheel equipped with 54 buckets. Exhaust from the turbine wheel is diffused in an exhaust cone to a lower velocity in the circular exhaust pipe of constant diameter, which carries the gas to a jet nozzle. In some installations, the exhaust pipe and exhaust nozzle have been combined into an exhaust pipe of constant taper from the exit diameter of the exhaust cone to the proper jet-nozzle diameter.

STRUCTURAL DETAILS

Table I gives some of the fundamental design data of the I-40 jet engine. Mechanical construction of the engine consists of five major subassem-

blies bolted together to form the complete assembly. These subassemblies are:

1. Accessory drive
2. Compressor
3. Turbine and combustion chambers
4. Exhaust cone
5. Air adapters

Each of these is a complete unit operative in itself in so far as its particular function is concerned; and each is interchangeable in all I-40 gas turbines without matching, balancing, or special fitting. The first three subassemblies may be tested independently—a distinct advantage in production, maintenance, and field service.

The complete assembly is mounted on two horizontal trunnions and a front support. The trunnions project outwardly between air adapters at the rear air inlet very near to the center of gravity of the gas turbine. The front support can be mounted on either the top or the bottom of the gear casing, depending upon the installation.

Accessory drive consists of an outer casing (which carries the various accessories) and a rotor cage which fits in the casing (carrying all the gears and most of the bearings). The outer casing also serves as the oil reservoir for the gas turbine.

The compressor rotor is comprised of an impeller with stub shafts bolted on each side. The front shaft is carried by a ball bearing; and the rear, by a roller bearing. Axial clearance is adjusted by a sliding ring which carries the outer race of the ball bearing. These bearings are carried in support casings, which bolt to the flanges of the accessory drive on one end and the turbine and combustion assembly on the other.

Table VI. *Fundamental Design Data*

Impeller diameter	30 in.
Impeller-inlet diameter	18¼ in.
Impeller-hub diameter	8 in.
Diffuser-throat area	75 sq in.
Fuel-nozzle size	40 gph at 100 psi
Turbine-nozzle area	121.3 sq in.
Turbine-pitch diameter	22 in.
Turbine-nozzle and blade height	4 in.
Exhaust-pipe diameter	21 in.
Jet-nozzle diameter	19 in.
Maximum over-all diameter	48 in.
Over-all length	101½ in.
Average weight	1,820 lb
Center of gravity (aft of trunnion)	2 in.

Truss rings are fastened to these same flanges and span the front and rear air inlets, supporting the compressor casings and the diffuser. The diffuser is a box-type single casting with the elbows and turning vanes cast integrally, and compressor casings form the side walls of the impeller and support part of the inlet guide vanes.

The turbine and combustion-chamber assembly consists of a turbine-bearing support, turbine rotor, and set of combustion chambers. The turbine rotor has a shaft flash-welded to the wheel and buckets dovetailed to the rim of the wheel. The rotor is carried by a roller bearing at the rear end and a ball bearing at the front end. The axial clearance is adjusted in the same manner as for the compressor rotor—by a sliding ring which carries the outer race of the ball bearing. The bearing support is covered with a shroud so that cooling air can be brought along the inner wall, then passing out through the cooling fan on the front side of the turbine wheel, cooling the turbine wheel, and finally emerging through the spaces of the combustion chambers.

The 14 combustion chambers are arranged around the turbine with their axis conical, joining together at the turbine inlet to provide an annular flow of hot gas. Turbine nozzles are mounted between two rings around the discharge of the combustion chambers. At the entrance end of each combustion chamber, a piston-ring joint is used to allow for expansion resulting from heating. The flange of the turbine-bearing support (which joins to the compressor assembly) and the flange around the turbine-nozzle ring (which joins to the exhaust cone) are connected by tie straps made of Invar to ensure that there will be no relaxation because of heat.

The outer cone of the exhaust-cone assembly supports an inner cone by four struts and is insulated on the outside by an aluminum-foil wire-mesh blanket. The outer-cone large front flange acts as a shroud for the turbine buckets, and the small rear flange connects to the exhaust pipe.

Air adapters, which are aluminum castings carrying the fuel nozzles, domes of combustion chambers, and spark plugs are so designed that they can be removed from the turbine for inspection of fuel nozzles, domes, and liners.

The lubrication system incorporates an oil pump comprised of two elements—lubricating and scavenger. The lubricating element draws oil from the reservoir in the bottom of the accessory-drive casing and passes it through a filter for delivery to the four main bearings, to the coupling sleeve between the turbine and compressor rotor, and to the quill-shaft splines of the accessory drive. Oil from the front compressor bearing and accessory-drive quill shaft drains directly into the oil reservoir. Oil from

the other three main bearings and coupling sleeve drains into a sump, from which it is drawn by the scavenger element, then delivered back to the oil reservoir. At a turbine speed of 11,500 rpm, the lubricating pump has a displacement of about 3 gpm, and the scavenger pump about 10 gpm. Last-chance screens are provided immediately ahead of all oil jets, to prevent plugging.

Gears and bearings in the accessory drive are lubricated by splash from the gear which drives the lubricating and scavenger pump. This gear—located under the oil level—is protected by a shroud, and a small amount of oil is admitted to the inside of the shroud through an orifice in the bottom. Thus, the quantity of oil for lubricating the gears and bearings is metered, and the oil in the reservoir is not churned into foam by the gears. The gear casing is vented by a pipe to a point aft of the baffle on the rear side of the rear compressor inlet. The vent opens into the accessory-drive casing near the center of the front side, and thus oil will not run out of the vent at any attitude of the gas turbine.

Performance Data

Take-off and military rating of the I-40 are for 15 min at 11,500 rpm. Normal rating is for continuous operation at 11,000 rpm. Idling speed is minimum continuous operating speed and is for 3,500 rpm.

In the accompanying charts, plots of thrust, fuel flow, specific fuel consumption, and exhaust temperature are shown for the 21 I-40 gas turbines built at GE's Lynn plant. Actual test points are plotted and corrected to standard conditions, and the single curve gives the average of the data.

Table VI lists the average performance data on the same basis of the curves, from which values for thrust, fuel flow, specific fuel consumption, and exhaust temperature are taken.

Table VII. I-40 *Gas-turbine Average Performance Data at* 11,500 *Rpm with Standard Inlet Conditions of* 14.7 *Psi* 59°F *and* 0 *Ram*

Thrust	4,000 lb
Fuel flow	4,740 lb/hr
Specific fuel consumption	1.185 lb/hr/lb thrust
Exhaust temperature	1170°F
Compression ratio	4.126
Compressor discharge temperature	413°F
Combustion pressure drop	3.18 psi
Turbine-inlet temperature	1492°F
Air flow	79 lb/sec

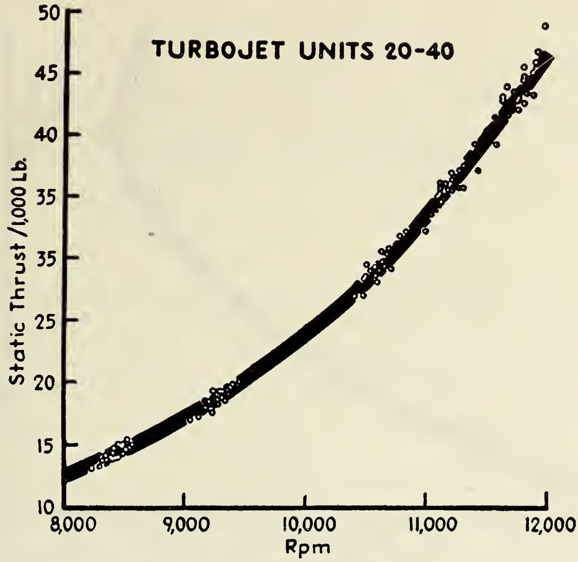


Chart of static thrust. Curve passes through 4,000 lb at 11,500 rpm.

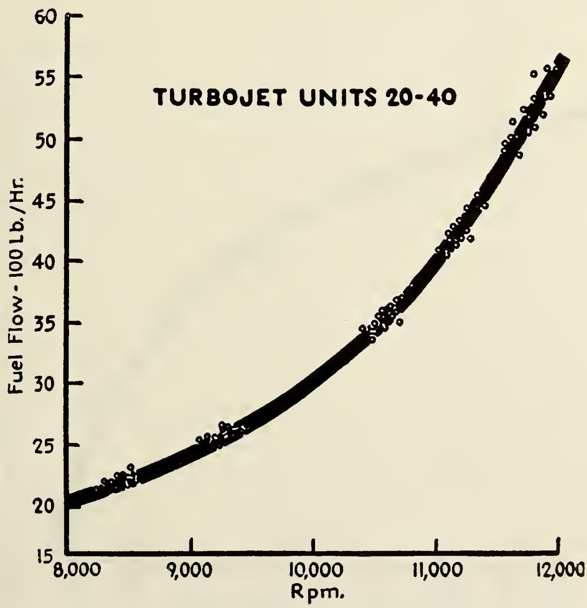


Chart of fuel flow. Curve passes through 4,740 lb 1 hr at 11,500 rpm.

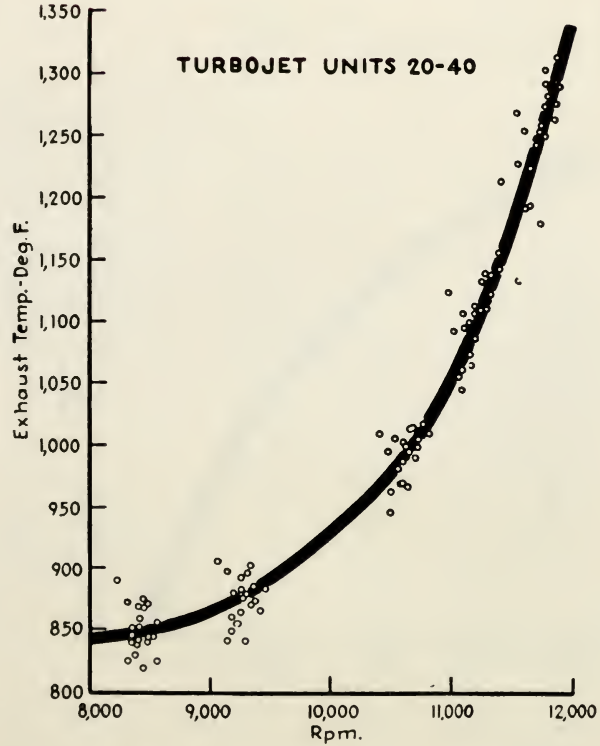


Chart of exhaust temperature. Curve passes through 1,170 deg F at 11,500 rpm.

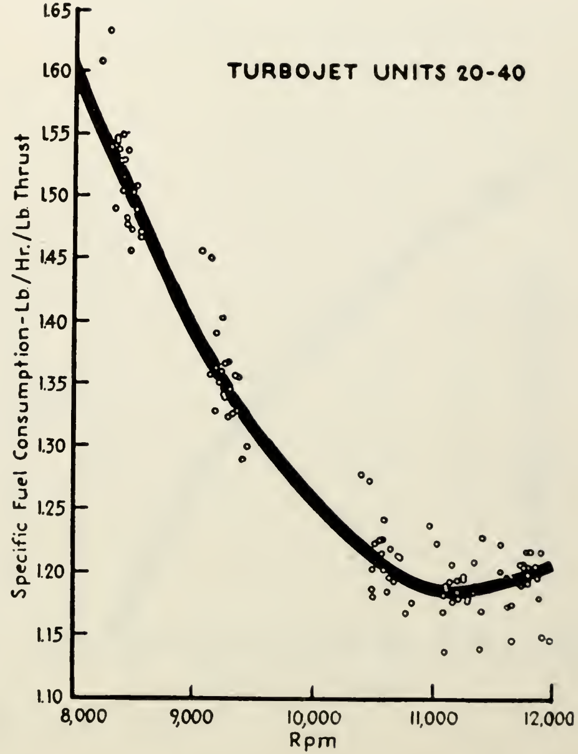


Chart of specific fuel consumption. Curve passes through 1.185 at 11,500 rpm.

CHAPTER FIVE

The Navy-industry Team Takes the Field

ALTHOUGH THE NAVY made no announcements on gas turbine-powered aircraft for nearly a year after the AAF's first disclosures, this branch of the service had not been ignoring the new type of power plants.

Nor had several industrial concerns which played vital parts in the Naval program. In fact, much of the initial work had been done independently even before World War II.

In the late 1930's, for example, Westinghouse Electric Corp. engineers had made studies on gas-turbine cycles and had even done some preliminary design work on marine applications. That company's Dr. Stewart Way, in completely independent research, made design studies on jet propulsion for aircraft in two forms—the turbojet and the athodyd—and is credited with originating the aviation gas-turbine activity now being carried on by Westinghouse. The study on the athodyd was completed in July, 1941; that on the turbojet, in August, 1941.

As far back as 1938 Allis-Chalmers Mfg. Co. gained background experience for aircraft jet propulsion when the company built the first successful gas turbine for power purposes in the United States with a unit which was applied to the Houdry process for production of aviation gasoline. The next year Allis-Chalmers started studies of aircraft jet-propulsion units, of which the basic power element was a gas turbine.

And early in 1941, John K. Northrop, president and chief engineer of the firm bearing his name, approached the Navy with a well-prepared proposal to develop a propjet. It was evident that development of such a power plant would require some time; but even at that late day, Navy budgets did not provide funds for such a project. However, since the AAF was also interested, a jointly financed contract was negotiated by the Bureau of Aeronautics in June of that year.

At about the same time that the Northrop project was being started, the Bureau of Aeronautics also contracted with Turbo Engineering Corp. of New York City for a comprehensive design study of gas-turbine components. Turbo Engineering was created largely by the efforts of Rudolph Birmann, veteran de Laval Steam Turbine engineer, to whom both turbo-

superchargers and gas turbines were an intellectual challenge; and it was largely through his offices that de Laval participated financially in the development organization. Working with Birmann were J. T. Tweedale and Arthur Moody, who headed the design and thermodynamics groups.

Under this contract, the primary parameters influencing turbine design, such as pressure ratio, turbine-inlet temperatures, individual-part efficiencies, intercoolers, heat exchangers, and other components, were systematically analyzed. The importance of the findings can be appreciated when it is realized that the mixed-flow impeller, for instance, developed pressure ratios of better than 6:1—and this on an 11-in. intake and 14.26-in. mean diameter. Tests on this compressor—which was made small, to employ supercharger parts—showed that it would have developed 1,128 lb static sea-level thrust for a weight of 375 lb.

Results of the Turbo Engineering study also proved important in guiding Bureau of Aeronautics policy, not primarily because of the specific design developed but in proving the thesis that, for aircraft application, the simplest possible unit appeared most attractive for that time—it eliminated the possibilities of becoming involved with intercoolers, heat exchangers, reheaters, and other such components, which were then of marginal usefulness because of weight and space penalties.

Early in April, 1941, shortly after the special NACA committee on jet propulsion had been organized by Dr. Bush, a subcommittee held preliminary discussions with AAF officials, Westinghouse, Allis-Chalmers, and General Electric engineers. That the discussions were preliminary, to put it mildly, is evidenced by one meeting when the industrial representatives were asked how large an appropriation they thought would be necessary to make a complete design study. A long pause followed while each company man waited, hoping that someone else knew the right figure. Finally, as was later learned, one man "reached out in the air" and hesitantly said, "About $100,000, I guess." Quickly the others agreed; and, since there was none among the government representatives who could name a better figure, the $100,000 stood, even though it proved to be but a small starting point.

On Apr. 22, only 12 days after the full committee's first meeting, R. C. Allen, manager of the Allis-Chalmers Steam-turbine Department and an original member of the committee, began discussions of the first proposal for the jet-propulsion engine.

A few weeks later, the committee recommended to Dr. Bush that this gas-turbine type be studied further. The committee took its own steps to continue study of the general subject by creating a subcommittee under Allen's direction.

Known as the "Turbine and Compressor Panel," it included Dr. L. W. Chubb, director of the Westinghouse Research Laboratories; Dr. C. R. Soderberg of MIT; Prof. A. G. Christie of Johns Hopkins University; and Dr. A. R. Stevenson of General Electric.

In July of that year, the panel concluded that it was advisable to pursue investigation of the jet-propulsion power plant, with various phases of the research to be conducted by General Electric, Westinghouse, and Allis-Chalmers. In September, this conclusion was offered as a resolution by the committee as a whole, recommending that projects of the three companies be developed toward contracts with the Army and Navy.

In October, the Navy Bureau of Aeronautics invited Allis-Chalmers to recommend procedures for starting work on a jet-propulsion unit and, in February of 1942, awarded the company a contract "to prepare a preliminary design for a jet-propulsion unit to determine if further development appears promising."

Design of the Allis-Chalmers engine, under the direction of Allen and Dr. J. T. Rettaliata, had progressed to the point where construction was about to be started, when the Bureau of Aeronautics requested a delay in favor of an active production program of a more completely developed British unit for a different class of service.

Meanwhile, Pearl Harbor was attacked; and early the morning after, Dr. Chubb and M. W. Smith, vice-president in charge of engineering, went from Pittsburgh to Philadelphia to a meeting with F. T. Hague, then manager of engineering, and R. P. Kroon, then manager of development engineering, of the Westinghouse steam-turbine division, to review, in the light of the events that occurred at Pearl Harbor, what that division of the company could best do in the war program. The very next day, W. F. Boyle, then manager of the Marine-application Department, was in session with the Navy's Bureau of Aeronautics in Washington and came back that afternoon with a "letter of intent" for a turbojet-design study based on the work done by Dr. Way. It said, in effect, "Give us a jet engine that will turn out the equivalent of 600 hp at 500 mph at 25,000 ft [which shows that the proposal was highly theoretical and way up in the clouds; ratings have settled to sea level since that time], and don't get involved with what anyone else may be doing."

How well that last point was observed—possibly because there was no time for snooping—is shown by the fact that no one in the small group of Westinghouse steam-turbine division engineers (outside management) even knew General Electric was working on a British design until the summer of 1943.

This small group, operating as the Development Engineering Department of the steam-turbine division, embraced only 14 engineers and nine skilled experimental mechanics. Dr. Way made the first design studies and, in cooperation with A. E. Hershey, has since been responsible for combustion research on all Westinghouse turbojets. Kroon became manager of engineering for the aviation gas-turbine division. Other members

The original group of Westinghouse engineers and technicians who designed and built the U.S. Navy's first turbojet. Front row, *left to right:* J. W. Rivell, C. Deiner, H. B. Saldin, K. B. Koster, V. Proscino, and W. D. Eckard. Center row, *left to right:* A. H. Redding, B. B. Anoschenko, J. F. Chalupa, C. A. Knapp, D. P. Darwin, C. D. Flagle, H. A. Jackson, W. R. New, C. A. Meyer, and W. H. Dickinson. Rear row, *left to right:* R. P. Kroon, C. C. Davenport, R. Gantz, A. S. Thompson, J. H. Borton, W. D. Kane, R. L. MacCartney, W. M. Keenan, J. S. Fieldhouse, J. L. Hall, G. W. Griebel, and O. E. Rodgers. (*Courtesy of Westinghouse Electric Corp.*)

of the team were: O. E. Rodgers, later to become manager of the Gas-turbine Design Department, who was made responsible for mechanical details and worked with A. S. Thompson, later to become section engineer in charge of the stress section; W. R. New, later to become manager of the Aviation Gas-turbine Laboratory, who did experimental work on turbine blades and instrumented and operated the first test call; A. H. Redding, later to become section engineer in charge of flow research, who designed the compressor; C. A. Meyer, later section engineer in charge of thermodynamics, who made the thermodynamic studies and the turbine design; Dr. C. C. Davenport, later section engineer in charge of the applied-mechanics section, who headed the bearing- and lubrication-system de-

sign; C. D. Flagle, later transferring to sales engineering, who was responsible for accessory design; D. N. Bradbury, manager of metallurgical engineering, who assumed responsibility for the development of materials for the various components; J. F. Chalupa, later to become section engineer in charge of the project-engineering section, who headed drafting and layout; and B. V. Anoschenko, section engineer, who was and still is in charge of the experimental laboratory, where much of the work on the original 19A engine was performed.

Working all hours of the day and night—and working many local subcontractors the same hours—they developed and built the first American axial-flow jet-propulsion engine, the 19A, a six-stage compressor, single-stage turbine engine which developed 1,200 lb static sea-level thrust for a weight of 830 lb, the 19 indicating the largest diameter of the engine. It made its first run on Mar. 19, 1943, and his fellow workers still insist that John Rivell, the operator, was as surprised and gratified as anyone else when it started. The first drawings, representing the transition from preliminary design actually to building an engine, had been made only the preceding September.

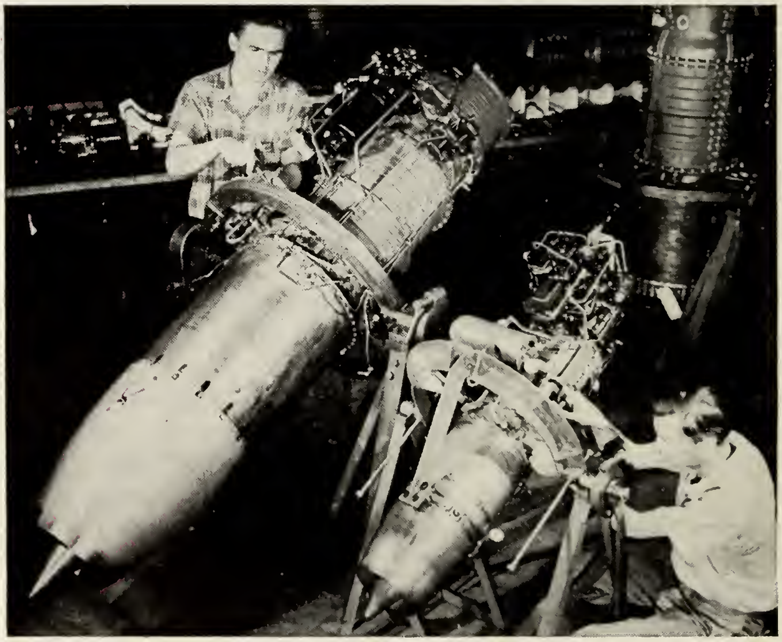
This first of the two 19A's, built by the experimental department, made its initial run in a small, "homemade" (according to present Westinghouse facilities) test cell which looked much like an old-fashioned outhouse. The engine completed its 100-hr endurance test on July 5, 1943, and, before being retired to the Naval Air Material Center Museum, ran a total of 137 hr. It was built as a booster unit for the Goodyear FG-1 Corsair, on which the second of the engines first flew on Jan. 21, 1944.

Since it was extremely difficult for one man to fly the plane and make tests on the turbojet, the Glenn L. Martin Co. was given a contract to modify a B-26 Marauder as the JM-1 so that the turbojet could be completely installed in the aft fuselage for testing by a crew that could accompany it.

From the very beginning, Westinghouse worked on axial-flow compressors, an interesting example of parallel research, for, though they didn't know it at the time, practically all of Germany's turbojet development work had been on this type. There were, however, two important reasons for working on the axial-flow type: (1) The company had a large backlog of experience with this type as the result of building steam turbines and blowers for Navy surface vessels of all types; (2) the basic requirement of high speed meant that diameter of the unit must be kept as small as possible.

Thus, the original 19A had its accessories housed within a fairing inside the intake casing, much as the starting engines are installed in the Jumo-

This Vought F4U Corsair served as the first flying test bed for the prototype Westinghouse turbojet, the first flight being made on Jan. 21, 1944.



Westinghouse 19-B Yankee (*left*) and 9.5 axial-flow turbojets (*right*). The 9.5 was used in the Navy's guided-missile program.

004 and BMW-003 units. The design, production, and maintenance headaches of such an installation were terrific, but it made possible an unequalled diameter-power ratio.

Out of this original design have grown at least four other Westinghouse turbojets: the 19B Yankee, first tested Mar. 15, 1944, with a thrust of 1,300 lb for a weight of 825 lb; the 19XB–2B, thrust 1,600, weight 710 lb; the 9.5A and B "baby" jets; the 3,000-lb thrust 24C; and a turboprop development, 25D, which has since been canceled.

Another Westinghouse project was a proposal calling for a complete design study of a gas turbine (developing the equivalent of some 3,000 hp) driving a high-speed contrarotating shrouded propeller at about the same time that the NACA at Langley Field initiated design and wind-tunnel testing of both shrouded and unshrouded multibladed contrarotating propellers. Simultaneously the Navy inaugurated a series of design studies for airframes to utilize this proposed powerplant.

These studies indicated that the engine could not be easily installed in an airplane, because of the fact that the propellers were of the pusher type and the CG of the engine installation would be too far back. The layout of an engine involving freely-rotating propellers is such that there are difficult problems in design and manufacture. As a result, only the original design study was completed, and efforts were directed to the turboprop mentioned above.

Principal difference between the 19A and 19B (a detailed study of which is given at the end of this chapter) was installation of the accessories outside the unit, so that it could be used as a prime mover rather than a booster; and changing from individual combustion chambers to an annular type. This latter change was brought about by two factors: In the original design the chambers were installed as a complete subassembly, which complicated both production and maintenance. More important, however, is the fact that the annular chamber has been found to be more efficient.

Even before the 19B design was proved, the Navy called for airframes to be built around it, inviting several companies to submit designs, with development of the engine and the airplanes proceeding in parallel. The McDonnell Aircraft Corp. design was chosen, its twin-engine FD-1 Phantom coming up as the Navy's first straight turbojet craft, which was, in late 1946, in production for carrier use. The Phantom left the ground the first time quite unofficially during single-engine taxi tests on Jan. 1, 1945, when the craft hopped about 6 ft into the air and flew a few moments before the startled pilot brought it back to the ground. The first official flights were made later that same day—one of 28- and the other

of 25-min duration. The Phantom was tested for carrier maneuvers in the summer of 1946 on the battle carrier (CVB) *Franklin D. Roosevelt.*

During this development period, the Navy called for a smaller unit to power guided missiles then being designed. From this request came the 9.5A, a scaled-down version of the 19B, having a six-stage compressor with a maximum speed of 34,000 rpm and delivering 275 lb static sea-level thrust. In addition to its use in the guided-missile program, this engine has functioned in the TD2N, a Navy radio-controlled drone, the

McDonnell Phantom, powered by two Westinghouse 19B's, was the U.S. Navy's first all-jet airplane and was its first to operate from a carrier.

control of which has been "passed" from one mother plane to another.

During 1946, the larger Westinghouse unit, 24C, underwent considerable test running, and in October was flight-tested in the Chance Vought XF6U-1 Pirate, and in April, 1947, in the McDonnell XF2H-1 Banshee (2 units). Present output is 3,500 lb thrust. A new unit of more than double this capacity is under development. Present rating is 3,250 lb.

The importance that Westinghouse places in the future of the aircraft gas turbine was emphasized by the creation, on Feb. 1, 1945, of the aviation gas-turbine division, with G. H. Woodard as manager. This is devoted exclusively to the production of gas turbines for aviation applications and is completely autonomous. W. B. Anderson became manager in May, 1947.

Meanwhile, the Northrop, Allis-Chalmers, and Turbo Engineering projects had been carried on independently.

The Northrop unit, in fact, became the Navy's first aircraft turbine-driven propeller unit when the full-scale model made its initial run late in 1944. Although performance did not come up to original design conditions, the unit did produce useful shaft horsepower. However, work on

the project was curtailed by the Navy, and further development was continued on a much reduced scale by the Northrop organization itself.

The Turbo Engineering Corp. had done an outstanding job on the design study, at the same time making a basic design for a two-stage turbosupercharger, with the result that the Bureau of Aeronautics negotiated a contract for design and construction of two turbojet engines to deliver approximately 1,000 lb static thrust for a weight of around 400 lb. This design, which appeared very attractive in 1942, embraced the previously mentioned single centrifugal compressor with mixed-flow impeller and a single-stage turbine with internally cooled blades. Such pressure was put on the organization to develop the supercharger further, however, that work on the turbojet lagged. This, coupled with other turbojet developments and a bottleneck in machine tools, caused the Navy to cancel the contract in September, 1944.

Shortly after the war, however, the de Laval Company evidenced more than passing interest in jet propulsion by establishing, in February, 1945, an aircraft gas-turbine division under Rudolph Birmann's direction.

Results of the Allis-Chalmers studies culminated in a ducted-fan design giving the conventional hot jet, surrounded by a cold jet from the first stages of the axial-flow compressor. Calculations indicated that the unit would operate at a much higher efficiency than the conventional single-path design and that the take-off characteristics should be better. Although the unit is heavier than the single-path type of engine, the specific weight is still less than that of the conventional engine and propeller, and the diameter is much smaller, resulting in reduced head resistance. The design studies on the double-path unit were not completed, for, in 1943, at the request of the Bureau of Aeronautics, Allis-Chalmers undertook the manufacture of the British de Havilland-Halford unit under license for both the Navy and AAF, designated H1-B.

A number of these engines were delivered to both the Army and the Navy and were flown in experimental military planes. Their reliability proved to be of the highest order, and efficiency was good.

During the period of investigation of the de Havilland unit, as requested by the Navy, Allis-Chalmers top engineering and production personnel had been flown to England to study de Havilland engineering and production methods. These men were: R. C. Allen; Fred S. Mackery, general works manager of the Allis-Chalmers general-machinery division; Dr. Retalliata, now director of the department of mechanical engineering at Illinois Institute of Technology; A. H. Case; R. Bruesewitz; E. J. Foley; J. L. Ray; Jack Kodler; T. L. Swanson; and Fred Agthe. The last seven of the group were in England at various times during the

Added to the Navy's jet-fighter list late in 1946 was the Vought XF6U-1 Pirate shown here with a predecessor type, Vought's F4U-4 Corsair, an outstanding reciprocating-engine fighter. The Pirate's power plant is the Westinghouse 24-C axial-flow turbojet engine. (*Courtesy of United Aircraft Corp.*)

German V-1 and V-2 attacks against the London area, where the Allis-Chalmers-de Havilland activities were centered.

As in the case of several other large firms, Allis-Chalmers' interest in jet propulsion was not simply a wartime phase, for in 1946 the company resumed its own development program, working on both straight turbojet and propeller-drive units under W. B. Tucker, D. Emmert, and A. H. Case.

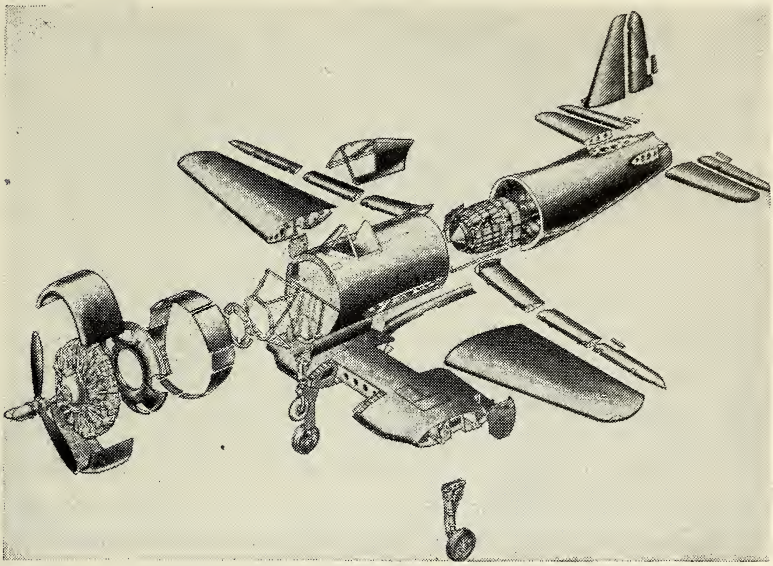
A cursory glance at naval gas-turbine developments during the early part of the war would seem to indicate that most of its eggs had been put in three baskets—Westinghouse, Allis-Chalmers, and Turbo Engineering. But such was far from the case; the Bureau of Aeronautics had con-

Official U.S. Navy Photograph

Ryan FR-1 Fireball in flight with its conventional reciprocating engine in the nose inoperative and propeller feathered, power being furnished by General Electric I-16 turbojet mounted in the fuselage aft of pilot. Speed with either engine is over 300 mph, with both, over 400.

tacts and contracts not only with many industrial concerns but with other government agencies as well.

In late 1942, for example, a contract was negotiated with Ryan Aeronautical Co. for a design embracing both a conventional reciprocating engine (to give necessary carrier take-off characteristics and cruising range) and a turbojet (to give the high performance essential for com-



Exploded view of Ryan FR-1 Fireball, showing installation of a 1,350-hp Wright R-1820 reciprocating engine in nose and a modified General Electric I-16 turbojet in the aft section of the fuselage. (*Courtesy of Ryan Aeronautical Co.*)

bat). Results of this tie-up were the "composite" engine Ryan FR-1 Fireball, the first plane in the world to combine the two types of power plant: the reciprocating engine being a 1,350-hp Wright R-1820 Cyclone; and the turbojet, mounted inside the fuselage aft of the cockpit, being a General Electric J-31 modified to use the same fuel.

High speed on either engine alone is in excess of 300 mph; on both, it is approximately 430, with high-performance characteristics at all altitudes on both engines. Although this craft did not get into combat, one squadron was in advanced training in the Pacific when the Japs surrendered. A newer model, the F2R, was revealed in January, 1947. It is powered by a General Electric T-31 (TG-100) turboprop of about 1,700 hp in the nose and a J-31 turbojet in the tail. The larger Allison-

Revealed early in 1947 was the Navy's Ryan F2R-1, a development of that company's FR-1 Fireball. The F2R-1 had a General Electric T-31 turboprop in the nose and, like the FR-1, a GE J-31 in the fuselage aft of the pilot's cockpit.

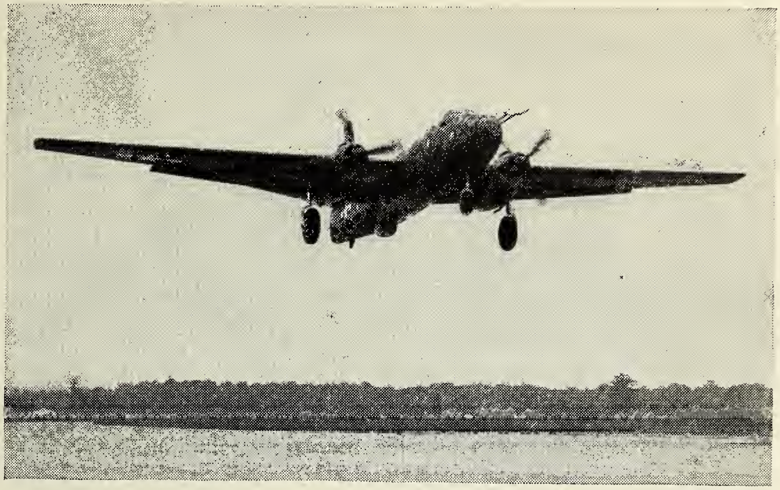
built General Electric I-40-4 is used in the Martin XP4M-1 patrol bomber; two of them at 4,000-lb thrust each forming a composite power plant with two 3,000-hp Wasp Majors. The axial-flow GE unit, TG-180, powers the North American FJ-1 carrier fighter and the Douglas 558 Skystreak.

Main reason for a design including both reciprocating and jet power plants was largely a matter of timing: When the specifications were first laid down, the then available turbojets and turboprops did not have fast enough take-off for carrier-based craft, and their fuel consumption was too high for the ranges already necessary. Swift advances in the gas-turbine art have, however, made it purely an "interim" design in so far

North American's FJ-1 Navy fighter, powered by a General Electric J-35. With a top speed of well over 500 mph, the craft's droppable wing tanks gave range considered absolutely essential when the craft was revealed late in 1946.

as naval aircraft are concerned, but the design opened new fields of exploration in the transport field.

Another development, a jet-booster installation for a larger type of plane built by Curtiss-Wright, reached the flight-test stage shortly after the war ended. This was the XF15C, which the Allis-Chalmers H-1B in the tail.



Navy patrol plane Martin XP4M-1 with two piston engines and propellers (Wasp Majors, 3,000 hp) and two turbojet engines (Allison J-33-4, 4,000-lb thrust) in the same nacelles. (*Courtesy of the Glenn L. Martin Co.*)

From the very start of the program, Navy policy was to have several projects going simultaneously—but independently—with correlation taking place when results became apparent. At first, naturally, all effort was expended toward getting turbojets and turboprops in the air. But, as soon as possible, a rounded program of research and development was inaugurated, ultimately reaching into many government agencies and industrial concerns. One industrial case was that of the Pratt & Whitney division of United Aircraft, long a large supplier of Navy aircraft engines.

Early in 1941, the engineers of this organization had become interested in the possibilities of the gas turbine as an aircraft power plant, and a separate research and development group was set up to explore these possibilities by L. S. Hobbs, now vice-president for engineering of United Aircraft but then engineering manager of the Pratt & Whitney division. This group was under the direct supervision of Val Cronstedt, executive engineer of Pratt & Whitney; and the consulting services of Prof. C. R.

Soderberg of MIT, for many years an authority in the turbine field, were secured. Construction of a big turbine test lab was begun in 1947.

Actual work was started in the fall of this same year and has continued since then, but the advent of the war shortly thereafter meant that it could not be expanded so rapidly as had been planned. It was thought that the principal aircraft-engine firms should apply their engineering effort almost exclusively to meet the tremendous demands for increased

Martin & Kelman Photograph

Curtiss XF15C-1 experimental fighter as it was delivered late in 1946 to the naval test center, Patuxent River, Md. A composite aircraft, it had a Pratt & Whitney R-2800 reciprocating engine in the nose and an Allis-Chalmers H-1B (Halford design) turbojet in the tail.

performance from the conventional power plants, and they were confined principally to this field. However, in 1945, Pratt & Whitney was given a contract to produce the Westinghouse 19XB unit (1,600-lb thrust), and at the same time Navy contracts were received for the continued development of turbines of Pratt & Whitney's own design.

As late as the spring of 1947, no details of this program had been revealed. However, the company has announced its intention of participating completely in this field; and it is known that A. V. D. Willgoos, chief engineer, is devoting his time exclusively to gas-turbine developments. It is also known that for the more simple combinations, Pratt & Whitney prefers the axial-flow form.

Because of its necessary interest in steam boilers and turbines, the Navy has for years studied combustion problems through its Boiler and

Turbine Laboratory which was, of course, swamped with projects under way before the aircraft gas-turbine program was started. Consequently, in July, 1943, the Bureau of Aeronautics started its own combustion-research project at the National Bureau of Standards under the direction of Dr. E. F. Fiock.

Tangible results in the form of several fuel-nozzle improvements; ram-jet combustion-chamber designs; development of a liquid-air injection system for turbojets; and a turbojet exhaust-reheat system were soon realized from this program; and tests were made on many possible turbojet fuels.

Additional combustion-chamber development work was done by Northrop in connection with its original turboprop-design study. Allis-Chalmers subcontracted with MIT for combustion-chamber research, a project headed by Prof. H. C. Hottell and, later, by Dr. G. C. Williams. Upon expiration of the Allis-Chalmers contract, MIT carried on under a direct contract with the Navy to obtain fundamental information for all contractors.

Out of this work came combustion chambers designed specifically for the Allis-Chalmers design and the Westinghouse 19XB; and a special chamber (in 1944) for ramjet units, which has since been used by at least four different contractors. Compressor studies have been made by the NACA, beginning in September, 1944, when a 19B compressor was made available, followed shortly by one from a 9.5A, in addition to combustion-chamber work done by this research organization.

Metallurgical investigations have taken a prominent place in the Navy's research and development program. Its own Engineering Experiment Station at Annapolis has for years been conducting research on materials at high temperatures under Bureau of Ships' sponsorship. Since October, 1940, though, much of its work has been on materials for gas turbines. Early in 1941, the Navy Coordinator of Research and Development requested the National Defense Research Council (later to become the Office of Scientific Research and Development) for further work on heat-resisting alloys; and in December, 1941, and January, 1942, the Bureau of Aeronautics also started metallurgical research projects at both Westinghouse and Allis-Chalmers as part of their development contracts.

Early in 1941, Allis-Chalmers began to build a 3,500-hp gas turbine for test operation at the U.S. Naval Engineering Experiment Station at Annapolis, primarily for the study of high-temperature conditions. By early 1946, this unit had successfully operated at the unprecedented temperature of 1450°F. Although jet engines and turbosuperchargers operate at temperatures equal to that for which the Annapolis turbine was de-

signed, both the jet engines and the turbosuperchargers are of the single-stage construction, whereby cooling can easily be accomplished on each side of the high-speed turbine wheel. Thus, the Annapolis turbine is the first multistage turbine designed for high efficiency to operate successfully at the high inlet temperature indicated.

In July, 1942, Allis-Chalmers made arrangements for a program of research on turbine-blade materials at Battelle Memorial Institute. The research program set up with Battelle included a complete review of all materials then known to be available for high-temperature service. It was in the course of these investigations that Timken Roller Bearing Co. developed the "16-25-6 Timken alloy" for the Allis-Chalmers multistage Annapolis turbine for high-temperature service. This alloy was later very extensively adopted for gas-turbine supercharger disks and for the wheels of many successful jet engines.

Coordination of all these projects was the responsibility of a small group of Navy officers and civilian personnel. Captain (then Comdr.) Ricco Botta, USN, was head of the power-plant design section, which included Capt. (then Comdr.) F. B. Kaufman, USN, as assistant head of the section, and a civilian, C. S. Fliedner, principal engineer, and was responsible for design of all aircraft engines, propellers, and power-plant installations. In December, 1942, Captain Botta was succeeded by Capt. (then Comdr.) S. B. Spangler, who had been head of the installation and accessories section.

Rear Admiral (then Comdr.) L. C. Stevens, USN, as deputy director of engineering for experiments and developments, served in a liaison capacity with all turbojet projects.

Coordination and administration of contracts was the responsibility of the experimental-engines section, power-plant design branch, which was headed, from August, 1942, till after war's end, by Comdr. W. T. Hines, USN. This branch proved an unusual training school for gas-turbine men. Lieutenant L. F. Smith, USNR, for instance, was later assigned to the operating forces as fleet expert on all gas-turbine power plants. Another was William Bollay, who was called from his aerodynamic research work at Harvard to active duty as an ensign in 1941. He was assigned as head of the group in the experimental section dealing with compressors, turbosuperchargers and all types of gas turbine engines and had, as an able assistant, Pierce T. Angell, civilian aeronautical engineer of the group.

By war's end, Bollay had been promoted to lieutenant commander and headed a research group divorced from problems of immediate urgency

so that it could undertake longer range projects and serve in a consulting capacity to producers of aircraft gas-turbine engines.

Another in this group was Lt. Edward M. Redding, USNR, who specialized in development of high-temperature materials and combustion research and has collaborated with Lieutenant Commander Bollay in preparing several fundamental turbojet studies.

During 1946, BuAer's interest in a centrifugal-flow type of turbojet engine came to light in its active cooperation with the program of Taylor Turbine Corp., New York, to erect, manufacture, test, and maintain Rolls-Royce aircraft gas turbines (principally turbine jets) in the United States. As a start, two Nene I turbojets and two Derwent V's were sent to this country. In December, 1946, one of the Nenes which was being tested at the Naval Air Material Center, Philadelphia, completed its standard 150-hr U.S. A-N type-test run at 4,500 lb of thrust. A second test at 5,000 lb was begun shortly afterward. To provide the technical help required in these American tests, J. P. Herriot, chief development engineer of Rolls-Royce, who saw the Derwent and Nene through their 100-hr type tests required in England, spent some weeks in this country. Dr. Stanley Hooker, Rolls-Royce chief engineer, and other specialists from the company also paid short visits to assist in the early stages of transplanting the Nene on this side of the Atlantic. The Navy is interested in the Nene for a new Grumman carrier-based fighter.

In the meantime, the Taylor staff, under the direction of Philip B. Taylor, president, and S. T. Robinson, vice-president, was engaged in redrawing to conform to American production practice the thousand or more important blueprints of the Nene engine sent over from England. (Packard went through this with the Merlin.) Actual production of the Nene in the U.S. will be at Pratt & Whitney, under license from Rolls-Royce, Taylor Turbine having sold its interest to Pratt & Whitney.

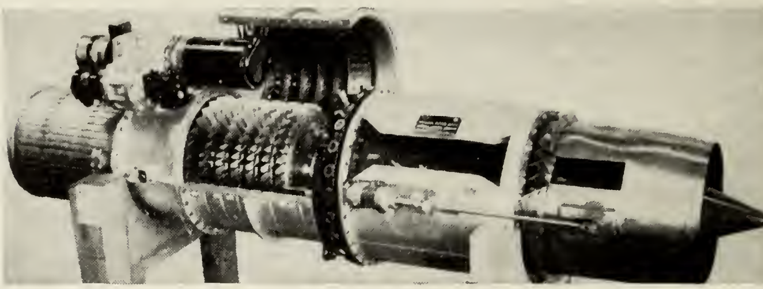
THE WESTINGHOUSE 19-B YANKEE TURBOJET [1]

Ordered by the Navy the day after Pearl Harbor, the first All-American-designed gas-turbine jet-propulsion engine was researched, designed, built, and tested by Westinghouse Electric Corp. in just 16 months.

Under Navy instructions, the small group of engineers from the Westinghouse steam division made no contacts with any other group engaged in jet work. Principal results of these instructions were twofold: They produced the first American axial-flow jet engine; and they brought forth

[1] From a design analysis by John Foster, Jr., which appeared in *Aviation*, January, 1946.

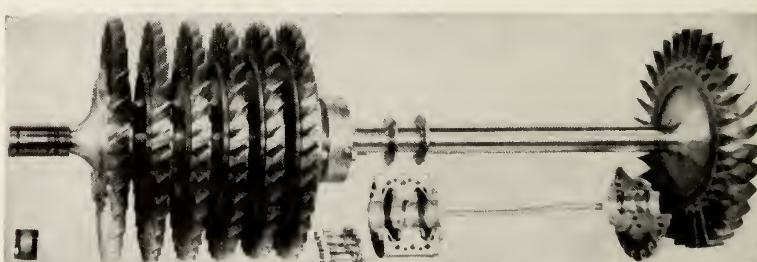
the most powerful engine in the world for its size—the 19-B Yankee. Later engines developed from the 19-A and -B, which are still held under military security, may be assumed to produce even greater thrust.



Cutaway view of Westinghouse 19-B showing: oil cooler; air inlet and front-bearing support (with accessories mounted atop it); six-stage axial-flow compressor; fuel manifold and thrust-bearing support; annular-combustion chamber; turbine; and exhaust cone. (*Courtesy of Aviation.*)

One of the prime design requirements—small frontal area—made it natural to select the axial-flow type of compressor. Aside from aerodynamic need, however, is the fact that a greater mass of air can be moved through the engine. In the 19-B, for example, the air takes less than 0.02 sec to pass from the intake, through the compressor, into the combustion chamber, through the turbine nozzle and turbine, and out through the exhaust cone.

On the 19-B, the annular aluminum oil cooler is bolted by a flange to the leading edge of the intake casting-front bearing support. Thus, the oil can be cooled even when the aircraft is stationary on the ground, but



Westinghouse 19-B compressor, shaft and turbine assembly, and bearings. (*Courtesy of Aviation.*)

no aerodynamic sacrifice is made. Two types of cooler have been provided to care for varied installations: one 24 in. long being built up of rectangular cross-section tubes, connected in series through cored flanges;

and one 9⅜ in. long, made up of spiral, rectangular, cross-section tubes. This latter type has been made standard.

The front, or No. 1, bearing support (corresponding to the intake casting of the Junkers Jumo-004 engine analyzed in the November, 1945, *Aviation*, page 115) is an aluminum casting comprising an outer ring with fore and aft flanges, connected to the bearing housing by four faired struts. These struts are constructed to house the accessory drive shaft, oil passages—both inlet and scavenge—for the main- and bevel-gear bearings, and air ventholes measuring compressor inlet pressure for the altitude compensator. A small spinner type of cap, quickly detachable by removing one screw, gives access to the accessory take-off-drive bevel gears without further disassembly.

On the 19-A engine, all accessories were housed within a fairing around the leading edge of the bearing housing, similar to the installation of gasoline starting engines on the Jumo-004 and BMW-003 engines. On the B engines, however, the accessories are attached to a gearbox fastened to a mounting face on the outside of the bearing-support casting.

The front bearing itself is a babbitt-lined sleeve split along the horizontal center line and grooved for oil passage. Sealing is effected by a combination pumping and labyrinth seal, which bolts to the aft face of the bearing housing.

The 55 inlet guide vanes are of rolled steel held by two steel-band shroud rings. Both roots and tips of the guide vanes are set in slots in the shrouds and welded in place. The outer shroud ring has four equidistant notches on the trailing edge, into which fit lugs that are screwed to the aft face of the casting to hold the ring in place. The inner ring is held in place by four safety-wired screws extending out through the inner ring of the casting.

Spindle of the six-stage compressor, including shaft at the inlet end and coupling flange at the discharge end, is machined from a single aluminum forging, with each disk having a double-convex cross section. Diameters of the disks range from 9.1 in. at Stage 1 to 12.85 in. at the final stage.

Compressor blades are machined-steel alloy with bulb-type roots. They are held in place in the milled disk slots by wire locking keys, which are turned up into the grooved sides of the blade root. Profiles of the blades are based on a straight-line circular-arc formula, giving a foil very similar to a laminar-flow design. In addition to the aerodynamic considerations, use of this airfoil has been found advantageous in that it is easy—and thus inexpensive—to machine.

Though having the same foil, blades in the first compression stage have greater chord than do the succeeding stages, all of which are identical except for blade length. Centrifugal stresses in the first stage at the 19-B's maximum of 18,000 rpm reach 30,000 psi, or some 50,000 *g*.

The cast-aluminum compressor casing is made in two halves, which bolt together via axial flanges. In addition to the flanges at either end for attaching to the front bearing support and mounting unit, respectively, the casing is reinforced by a circumferential rib and two axial ribs spaced at 90 deg from the mating flanges of the halves.

The inside of the casing has six machined grooves—five to take stator-blade shroud rings; one, for straightener vanes. In most cases, the steel stator blades are cast, though some are rolled. The blade ends go through slots in the stainless-steel shroud rings and are gas-welded in place. Sealing rings, also of stainless steel, are formed by flanges welded to both edges of the inner shroud rings. The complete stator-blade units are held in place by retaining screws at the base of the mating flanges.

The straightening-vane assembly consists of three rows of vanes of NACA 6512 section, with construction like that of the stator assemblies, except for the sealing rings. This three-row design has been found most satisfactory, not only for skimming off boundary-layer air but for keeping up compressor efficiency and preventing choking.

Pressure rise across each set of rotor and stator blades is equal, the total compression being just over 3:1.

Backbone of the 19-B is the fuel manifold and thrust (No. 2) bearing support, a built-up, stainless-steel unit consisting of three concentric rings tied together by eight hollow, streamlined struts.

The outer single-walled, 5-in.-long ring has two welded flanges—that on the intake end supporting the compressor casing, that on the exhaust supporting the combustion chamber.

Welded to the front flange of this outer ring are the four engine-mount lugs, $2\frac{13}{16}$ in. aft of the center of gravity. When installation permits use of all four lugs, the engine-mount system will withstand all flight loads for the power plant itself but not those imposed by deflections of the airframe. A preferable mounting system calls for use of the two top lugs and of the auxiliary compressor flange for stabilizing in a vertical plane.

The middle of the three rings serves to split the air to streamline its flow into the combustion chamber as well as to function as the fuel manifold ring and support for the burner basket. The 24 fuel nozzles, of 9.5 to 12.5 gpm capacity, are installed on the machined aft face of this ring.

In some installations, the spray angle is set at 45 deg; in most others, it is 80 deg. In early installations, each of the nozzles was protected by 80-mesh screen strainer, but this has since been changed to 120 mesh.

The inner ring, which converges toward the rear, extends 6 in. into the combustion chamber and, for the most part, is single-walled. The thrust-bearing support is welded to the inner ring, forming a double wall at the support. At the forward end of the ring there is an axial flange, to the inside of which are welded 18 anchor nuts for securing the inner connecting cylinder. At the rear end of the ring is a flange drilled to take 16 tap bolts for securing the rear (No. 3) bearing support.

Extending between inner and outer rings along the aft face is a 6- by 6-mesh per sq in., 63 per cent open-area screen which creates turbulence and mixing of the air flow to the combustion chamber.

Seven of the eight struts connecting the rings provide passages as follows, reading in clockwise direction from the intake end:

Struts 1, 2, and 8—Leading edge drilled to mount thermocouple for measuring compressor-outlet temperature
Strut 3—Passages for leads of rear-bearing oil-outlet thermocouple
Strut 4—Inlet oil line to thrust (No. 2) and rear (No. 3) bearings
Strut 5—Two oil-return lines from Nos. 2 and 3 bearings
Strut 6—Passage providing for leads of thrust-bearing outlet thermocouple

Flanged to the fuel manifold-bearing assembly is the annular combustion chamber, a built-up, welded cylinder comprised largely of normalized stainless steel.

Complete details of the combustion chamber may not yet be revealed, but it can be said to include a perforated conical burner ring so designed that the turbulence created gives complete combustion at the high velocities developed in the 19-B. One feature is direction of a layer of cooling air along the inner surface of the casing shell so that temperatures of the casing do not exceed 400°F.

The turbine-nozzle assembly is composed of 45 Vitallium nozzle vanes held loosely—to permit thermal expansion—in slots in concentric steel shroud rings, the whole unit fitting into the rear of the combustion chamber between the No. 3 bearing sleeve and the outer casing. The outer shroud ring is machined to fit below the chamber flange face, thus facilitating attachment of the exhaust nozzle. This shroud ring is held in place by four lugs, similar to those on the inlet guide-vane assembly; the inner ring, by six tap bolts, also similar to those on the inlet guides.

General Specifications

Performance

Thrust, static sea level, 1500°F turbine-inlet temperature.	1,365 lb
Thrust, 500 mph, 1500°F turbine-inlet temperature......	1,125 lb
Air flow, static sea level, maximum....................	28 lb/sec
Air flow, 500 mph, maximum........................	38 lb/sec
Temperature at turbine nozzle, maximum..............	1500°F
Temperature at turbine nozzle, normal................	1200°F

Dimensions

Length, tail cone out, with oil cooler..................	104 15/32 in.
Length, tail cone out, without oil cooler................	80 15/32 in.
Diameter, basic......................................	19 in.
Diameter, maximum...................................	20 3/4 in.
Center of gravity, forward of mounting lugs............	2 in.

Weights

Dry weight, power plant.............................	765 lb
Oil cooler..	20 lb
Generator..	35 lb
Hydraulic or vacuum pump..........................	6 lb
Total dry weight................................	826 lb
Oil (3 gpm).....................................	21 lb
Total installed weight...........................	847 lb

Clearances

Bearings:	
No. 1, radial....................................	0.005 in.
No. 2, axial, thrust face..........................	0.000 in.
No. 2, axial, unloaded face........................	0.008 in.
radial....................................	0.005 in.
No. 3, radial....................................	0.005 in.
All bearing seals................................	0.008 in.
Compressor:	
Axial between rotor and stator blades...............	3/32 in.
Axial between inlet guide vane and first compressor stage..	1/8 in.
Radial between rotor-blade tips and casing...........	0.030
Radial between stator-shroud seal and rotor land......	0.030
Radial between straightener-vane seal strips and rotor land......................................	0.020
Turbine:	
Axial between nozzle inner shroud-ring turbine disk...	1/4
Axial between turbine disk and tail-cone assembly....	1/4
Radial, blade tips and exhaust-cone shell............	0.0625

Turbine-nozzle vanes:
Loose fit, cold, 0.010-in. clearance in shroud-ring slots.. 1/32-in. end play

Normal Temperatures and Oil Pressures

	12,000 rpm	18,000 rpm
Turbine-inlet temperature	800-1000°F	1000-1200°F
No. 1 bearing oil outlet	90-100°F	110-140°F
No. 2 bearing oil outlet	135-165°F	190-235°F
No. 3 bearing oil outlet	160-190°F	185-215°F
Fuel-pump discharge pressure	250-280 psi	
Fuel manifold pressure	30-35 psi	
Oil-pump discharge pressure	50-60 psi	

Turbine disk, shaft, and coupling flange are machined from a single Cyclops, 19-9-W-MO forging. The shaft coupling has a machined face, with counterbored and chamfered female spigot for positive alignment, and is attached to the compressor by ten ½-in. fitted bolts. No universal joint effect has been found necessary in the coupling.

Aft of the coupling are two vertical-thrust faces, finish machined and polished from an increased shaft outside diameter, for the thrust (No. 2) bearing. Just forward of the disk is the polished journal for the turbine (No. 3) bearing.

As on the compressor, the 32 turbine blades—K-43-B machine and hand-finished forgings—have bulbroots fitting into milled slots in the disk and are held in place by peening the shank of the root into chamfers at each end of the slots.

The thrust bearing—which also carries radial loads—is made up of a cast-steel housing containing lubricative- and scavenge-oil connections and holding babbitt sleeves and babbitt-covered radial faces to take the axial thrust. The turbine bearing is a cast-steel housing split along the horizontal outer line, with a babbitt-lining sleeve grooved for oil passage. This housing is drilled and cored for both lube and scavenge passages. Bearing seals of both thrust and turbine bearings are similar to those on No. 1 bearing.

Outer casing of the exhaust nozzle is stainless steel with a welded flange at the leading edge holding it to the aft combustion chamber by 32 bolts. Surrounding the casing at the turbine-blade trailing edges is a welded 1-in. steel ring to give greater stiffness to the unit in an area where clearance between blade tips and the casing is approximately 0.0625 in.

Inside the exhaust-nozzle casing are four hollow, streamlined struts supporting the movable tail cone, the motion being imparted through a pivot and linkage coming out through one of the struts to connect with an electric actuator installed on the combustion-chamber casing.

The movable cone gives greater operating efficiency, especially where rapid acceleration is required. In the cone-in position for starting and idling, the exhaust area is greatest, reducing pressure immediately aft of the turbine and making available the full pressure drop available to the turbine. In the cone-out position, the outlet area of the exhaust nozzle is reduced, and back pressure on the turbine increased, thus reducing available energy to the turbine so that higher temperatures and more fuel are required to maintain rotative speed. The additional energy thus delivered to the jet is realized in the form of an increase in velocity of the flow through the reduced nozzle area.

Accessories for the 19-B include: electric starter, generator, fuel pump, oil pump, governor, vacuum or hydraulic pump, and tachometer generator, all mounted on an aluminum-casting gearbox containing a train of 12 gears.

To give greater leeway in 19-B installations, the gearbox can be placed on top, bottom, or either side of the engine simply by attaching the front bearing support so that the drive shaft from the bevel gears points in the desired direction.

The governor, designed to protect against overspeed, is of the mechanical flyweight type. As it rotates at high speeds, centrifugal force on the weights increases and exerts an increasing force on the governor spring through toes on the weights. When this force overcomes the force of the spring, the governor stem moves up till the force of the weights equals that of the spring. Motion of the stem is used to control fuel flow through a balanced relay valve designed so that flow is straight through; and when rotative speed is increased to the point where the stem is moved up, the valve is forced into the fuel path, restricting flow to the burner. As the valve is forced into the fuel path, pressure is raised before the valve, this increase in pressure opening the relief valve to by-pass fuel not required. Both ends of the relay valve have spiral washout grooves to reduce pressure wedging and to clear out dirt that might cause the valve to stick. To prevent rapid closing of the valve, with consequent governor instability, an orifice is installed in the leak-off line from the bottom of the relay, giving a dashpot action which prevents the valve from moving faster than the engine can respond.

Pressure lubrication is provided by a four-element pump, one element for delivering oil to the bearings; three, for scavenging. The pump draws oil from the tank and pumps it through the filter, relief valve, cooler, bearings, and accessory gear case. A check valve is provided between the scavenge pump and tank, so that the latter can, if necessary, be installed above the engine center line.

Lubricating oil is fed to the front bearing support through a $\frac{1}{16}$-in. orifice and is also distributed via drilled passages to the accessory spiral bevel gears and the high-speed horizontal bearing assembly. Oil enters the front bearing through a $\frac{1}{4}$-in. hole, is sprayed on the bevel gears by a nozzle with a $\frac{1}{32}$-in. orifice, and enters the high-speed bearing assembly through a passage with a 0.021-in. orifice.

Accessory drive-shaft bearings are lubricated by oil leakage from the accessory drive shaft, as oil from any of the four inlets in the front bearing support and gearbox lubricates the bearings as it flows to scavenge points.

A line to the accessory gearbox has a $\frac{1}{16}$-in. orifice supplying high-pressure oil to a fitting in the front bearing support, from where an internal passage delivers it to a spray nozzle.

Thrust- and turbine-bearing oil is piped to fittings on the fuel manifold-support assembly, where it goes through internal piping to the forward face of the bearing support adjacent to two holes in the thrust-bearing housing. A cored aluminum cap, bolted to both support and housing, forms a passage across the joint of those two units and feeds oil through two holes—one into the thrust bearing; the other, via a $\frac{3}{8}$-in. tube, to the turbine-bearing housing. The internal piping proportions the oil between thrust and turbine bearings.

Pilot controls are reduced by having the gear type of fuel-pump output delivered to a barometric relief valve, sensitive to both total air pressure and fuel pressure, to regulate the fuel pressure before throttle and governor. From the barometric valve, the fuel goes through the governor and throttle, then through a dump valve, into the manifold and through the nozzles into the combustion chamber.

The piston in the dump valve is spring loaded open and is closed by admitting fuel-outlet pressure to the opposite side of the piston. Thus, when fuel to the pump is cut off, the valve opens, and fuel is scavenged from the manifold to prevent fire in the combustion chamber when the engine is shut down.

Since the engineers charged with developing the 19-B had to work entirely without reference to other American turbojet projects, they were, to put it mildly, on a spot. The resulting power plant is a tribute to the maintenance of the courage of their convictions, for, with less than half the weight and about half the length and diameter, the engine delivers nearly 70 per cent as much thrust as enemy axial-flow types which had been under development at least three years longer. The Yankee might well be termed an engine "radical in aerodynamic design, conservative in mechanical design."

CHAPTER SIX

A Big Boost from Government Research

Because virtually everything the NACA did during World War II was either "confidential" or "secret," there was little to indicate publicly that it was doing anything about jet propulsion. Just the opposite was the case, for this government research agency was literally up to its ears in jet-propulsion studies.

In fact, NACA first moved into the jet-propulsion field nearly a quarter of a century ago, for, in 1923, its *Report* 159 published the results of a study that had been conducted by the National Bureau of Standards at the request of the AAF. Written by Edgar Buckingham, this report concluded that "propulsion by reaction of a simple jet cannot compete, in any respect, with airscrew propulsion at such flying speeds as are now in prospect."

As can now be seen, such a gloomy conclusion was inevitable, because the nation's lack of air-power policy following World War I had practically stifled research and development, so that the speeds then in prospect were only about 250 mph, and computations indicated that the jet would take about four times as much fuel as would a reciprocating-engine-driven propeller unit.

This stifling of aeronautical research was strikingly illustrated by NACA's own position. It was established in 1915 by Congress "to supervise and direct the scientific study of the problems of flight with a view to their practical solution" and to "direct and conduct research and experiment in aeronautics." But, to carry out the program, Congress appropriated the insignificant sum of $5,000 annually for 5 years.

Throughout its career, however, NACA has been most fortunate in the high caliber of its 15 members appointed by the President, for these men —outstanding civilians and high military leaders—have nurtured its growth so that today its Washington headquarters staff directs a wide range of research activities of some 6,500 employees in three principal laboratories: at Langley Memorial Aeronautical Laboratory at the Army air base, Langley Field, Va.; Ames Aeronautical Laboratory at the naval air station, Moffett Field, Sunnyvale, Calif.; and the Aircraft-Engine Re-

search Laboratory on the municipal airport, Cleveland, Ohio. The first two are devoted chiefly to basic aerodynamic and flight research; the engine laboratory is concerned with aircraft propulsion. Just how important jet propulsion is can be appreciated from the fact that inspection of the Cleveland installation—possible only since the end of World War II—shows very few reciprocating engine studies under way but a myriad of jet projects, some of which might well make the layman think he had wandered into Buck Rogers' own laboratory.

But these developments were not all war babies; NACA's laboratories had, since 1923, not only been helping to develop airplanes that could reach the speeds required to make jet propulsion feasible; they had been carrying on development in the power plants themselves.

In 1939, for example, Dr. Vannevar Bush, then NACA chairman and later chairman of the National Defense Research Council, directed the Langley laboratory to proceed with a secret project that calculations had indicated would produce airplane speeds of more than 500 mph. The AAF, the Navy Bureau of Aeronautics, and NACA each considered the related problems in the light of their own spheres of activity. NACA was charged with the basic research and to plan it so that, when the time was ripe, information would be available to industrial designers to create an aircraft gas-turbine jet unit.

Meanwhile, Eastman N. Jacobs, of the NACA staff, had made a theoretical study based on Buckingham's work, his calculations covering the use of a reciprocating-engine-driven compressor completely enclosed within a fuselage and of the same diameter as the engine itself. In this scheme, it was planned to use all the heat from the combustion of the fuel in the engine, whether it was from the exhaust itself or from the air used to cool the cylinders. In addition, fuel would be burned as it was expelled from the compressor to obtain additional thrust.

On the basis of the Jacobs study, an experimental project was set up at Langley, using a 600-hp radial air-cooled engine to drive the compressor. The unit, which today looks terribly cumbersome, somehow acquired the name "jeep." Though fuel consumption of this strictly laboratory model was some five times that of today's turbojets, its tests proved extremely useful in solving many of the basic problems of burning fuels at very high velocities.

The Jacobs study showed that a jet-propulsion unit, utilizing an efficient reciprocating gasoline engine to drive a compressor and having a duct system of reasonable efficiency, was the most desirable experimental approach to the problems of jet-propelled airplanes. An airplane using this system would, it was shown, be capable of realizing truly high powers

from a high-temperature jet for short periods and would, in addition, be capable of moderately long cruising flight.

We may well, in fact, see something of a return to these very principles through development of the composite engine, as will be shown in a later chapter.

In developing and testing the jeep, combustion problems came to the fore, especially those associated with maintaining and controlling combustion in high-velocity air streams.

Fundamentally, the combustion problem appeared simpler than in reciprocating engines, because there were no octane requirements for the fuel—"pinging" simply wasn't there. The main difficulty was that of maintaining steady combustion of a mixture of fuel and air in a moving air stream. This seeming simplicity was at first deceiving, for it was soon found that the amount of fuel to be burned in the space available required a greater rate of heat release per cubic foot of space than had ever before been attained—in industrial furnaces, reciprocating engines, or velox boilers.

In addition, the flame speed of approximately 100 fps common to reciprocating engines limited the speed at which combustion could be maintained. This meant that research was necessary to learn how to support combustion over a wide range of conditions and at high velocities and at the same time carry the combustion through to completion in a short space.

A program devoted exclusively to combustion was therefore established. In order to make the experiments with approximately full-scale equipment, a blower driven by an airplane engine was to be employed; this would also make it possible to study the use of the engine exhaust if it should prove to be desirable to make use of the exhaust in connection with the burners. At the same time, the full-scale equipment was being built, though some experiments, which later proved very valuable, were conducted with small-scale units which could be more quickly set up.

This was about the time the first Whittle engine was ready for its first flight tests, and General Arnold and Admiral Towers urged NACA to accelerate its jet program.

As a result, in April, 1941, a telegram went to California to Dr. William F. Durand, who had been NACA chairman during World War I and largely because of his earlier work with turbosuperchargers an outstanding authority on the turbine type of machinery. Dr. Durand immediately heeded the telegram and, at the age of eighty-three, came out of retirement to help organize America's jet program for the war which was then

inevitable. On his arrival in Washington, he found that he was to be charged with the initiation of a greatly accelerated program of research and development in gas turbines for jet propulsion and propeller drive. It was to be separate from the Army's arrangements for licensing and manufacture of the Whittle type of unit, which, as we have seen, was entirely a result of British-AAF-General Electric-Allison teamwork.

Dr. William F. Durand (*left*) is congratulated at a New York meeting by Gen. Ira C. Eaker on receipt of the ASME Medal for 1945, "in recognition of his work in forwarding the design and application of principles of jet propulsion." Dr. Durand came out of retirement at the age of 83 shortly before the war to spearhead America's jet-propulsion research and development program.

NACA immediately set up a special committee headed by Dr. Durand to review available reports on the Whittle engine. On the committee with Dr. Durand were Prof. C. Richard Soderberg of MIT, as vice-chairman; R. C. Allen, chief engineer of the Steam-turbine Department of Allis-Chalmers Mfg. Co.; Dr. L. W. Chubb, director of research for Westinghouse Electric Corp.; Prof. A. G. Christie of Johns Hopkins University; Dr. Hugh L. Dryden of the National Bureau of Standards; General Echols, AAF; Capt. S. M. Kraus, Navy Bureau of Aeronautics; and Dr. Stevenson, Jr., of General Electric. Ex officio members were Dr. Bush; Dr. Jerome Hunsaker, later NACA chairman; Dr. George W. Lewis, NACA's

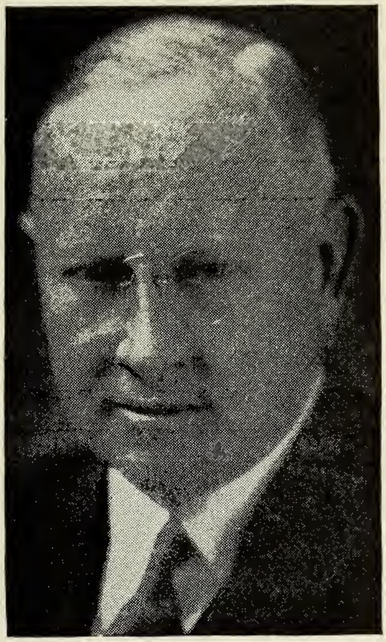
Dr. Jerome C. Hunsaker, Chairman of the NACA.

director of research; and Dr. George J. Mead, chairman of NACA's committee on aircraft power plants.

To promote the most extensive research progam possible, this committee recommended that the principal manufacturers of turbine machinery should each concentrate on one particular type of design. As has been seen, the Navy made agreements with Westinghouse, Turbo Engineering, and Allis-Chalmers; the AAF gave additional work to General Electric. NACA itself was to continue development of a unit using a reciprocating engine to drive the compressor, since this, together with testing equip-

ment designed by the organization, would provide information with which to compare the other designs.

Dr. Durand was instrumental in enlarging the scope of work being done at Langley; the test setup became more nearly a mock-up of a proposed airplane for ground testing rather than merely a burner test rig. A more powerful engine—825 hp—was obtained from the Navy, but



Dr. George W. Lewis, long-time Director of Research for NACA. (*Courtesy of Aviation.*)

most of the parts that had already been built were retained. The investigation was broadened to include a study of the compressor and duct characteristics as well as the combustion itself.

To save time, cheap and simple sheet-iron construction was used wherever possible, for even with this material it was hoped that something could be learned about how much fuel could be burned without producing excessive temperatures in walls and structural parts.

Preliminary tests were completed in July, 1942; and the results, together with a study of the possible applications to military aircraft, were reported to the committee on Oct. 6 of that year.

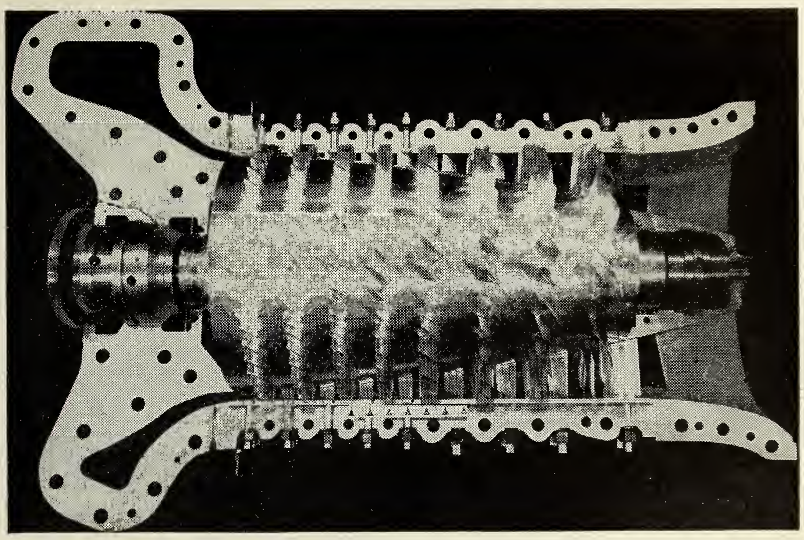
The report was distinctly encouraging—a 900-lb thrust from the compressor alone; by burning extra fuel in the jet, a thrust of more than

NACA "Jeep," one of this country's first jet-propulsion research projects, which provided invaluable data and helped the nation overcome the long lead that the Germans gained by starting their program in the thirties. (*Courtesy of NACA.*)

NACA "Jeep" in action at NACA's Langley laboratory. This unit was intended for preliminary studies in jet propulsion and the burning of gasoline by atomized injection in a high-velocity air stream. (*Courtesy of NACA.*)

2,000 lb was obtained. The large thrust, and the techniques developed, proved to be invaluable for NACA research and studies of complete gas-turbine units that were to be investigated in more complete facilities later made available with the establishment of the NACA Engine Research Laboratory, Cleveland, now known as the Aircraft Propulsion Research Laboratory, of which Edward R. Sharp is Director.

At the same time, beginning in 1940, NACA had inaugurated a program on centrifugal superchargers that had considerable effect on coordinating and speeding the turbojet program. A special subcommittee



Eight-stage axial-flow compressor, developed as part of NACA's basic research program. (*Courtesy of NACA.*)

for this study was headed by Val Cronstedt of Pratt & Whitney division of United Aircraft and included Robert P. Atkinson, Allison division of General Motors; Rudolph Birmann of Turbo Engineering; R. S. Buck, Pratt & Whitney; Opie Chenoweth, AAF Matériel Command; Kenneth Campbell, Wright Aeronautical Corp.; Oscar W. Schey, NACA; Dr. Chester Smith, General Electric; Lt. Comdr. S. B. Spangler, Bureau of Aeronautics; and two ex officio members, Dr. Lewis and S. Paul Johnston, then coordinator of NACA research, later a Navy captain and now director of IAS.

Immediate objective of this committee was to improve supercharger efficiency so that American warplanes would have superior altitude performance. As a result of cooperative efforts between NACA research activities and development facilities of Pratt & Whitney and Wright, a

method was developed by which it was possible to determine the absolute performance of a supercharger compressor.

When the committee was first set up, tests of the same compressor by different agencies were found to give different results. It was more of a job than might be thought to develop a standard method, without which it was impossible to tell whether or not one was actually getting more compressor efficiency. Designated as the "NACA standard procedure for testing and rating compressors," it became a base line that helped bring marked increases in efficiencies of compressors used on production engines—either centrifugal or axial flow—and served as the starting point for an intensive research program on compressors.

As proof of the importance of a wide basic aeronautical research program, another project under way at Langley played an important part in contributing to high performance of jet units. National Advisory Committee for Aeronautics engineers had long been convinced that high-efficiency compressors could be designed by applying aerodynamic principles; and as far back as 1938, Jacobs and Eugene M. Wasielewski had begun an investigation to determine the performance of an axial-flow compressor based on then available information gained from extensive research on airfoils.

Their theories were applied to the design and construction of an eight-stage compressor that was tested over speeds ranging from 5,000 to 14,000 rpm and with a range of air flows from full throttle to surge for most of the speeds—the highest were impossible to reach because sufficient power to drive the compressor was not available.

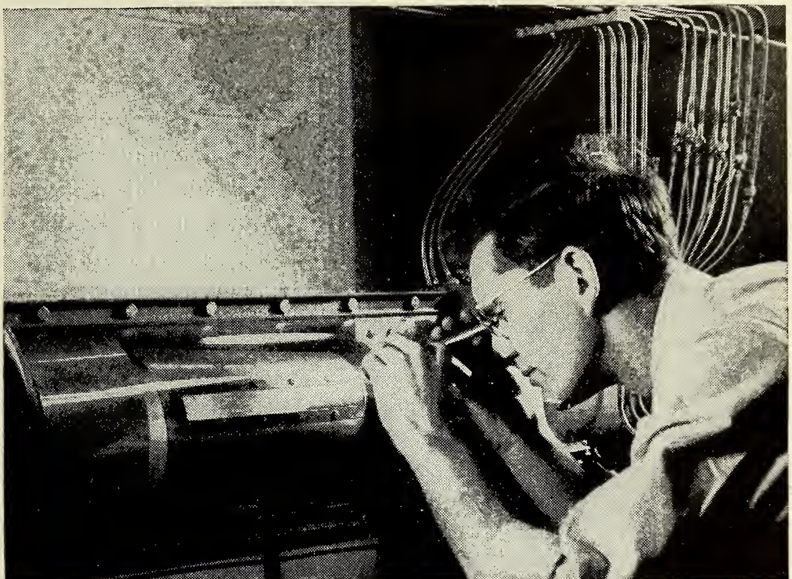
General Electric played an important part in this project, particularly in the design and construction of journal and thrust bearings to replace the original ball and roller bearings. As the importance of the results become apparent, increased power facilities were made available for driving the compressor at its design condition.

The tests showed this unit to be, in its day, one of the most efficient axial-flow units ever built. And, as late as mid-1946, the compressor was still undergoing tests aimed at achieving even higher efficiencies.

Another aspect of NACA's basic aerodynamic-research program that speeded turbojet development was its investigation of ducting to determine the most efficient means of taking large quantities of air into the power plant, having the ducts perform their function of cooling and supplying combustion air, and discharging them. Ducting research has, of course, been intensified by the advent of jet propulsion; and, although it is mainly an aerodynamic problem, the findings affect not only the performance of the turbojet itself but the actual drag of the airplane.

The long series of investigations on handling cooling air, a series begun back in the early thirties, provided a large backlog of information that was applied to turbojet problems.

Although all three of NACA's laboratories have worked on problems directly connected with jet propulsion, a large part of the work has naturally been done at the Engine Research Laboratory in Cleveland.



Official Photograph, NACA

Engineer at NACA's Engine Research Laboratory at Cleveland studies a jet-propulsion combustion unit through a specially designed transparent section.

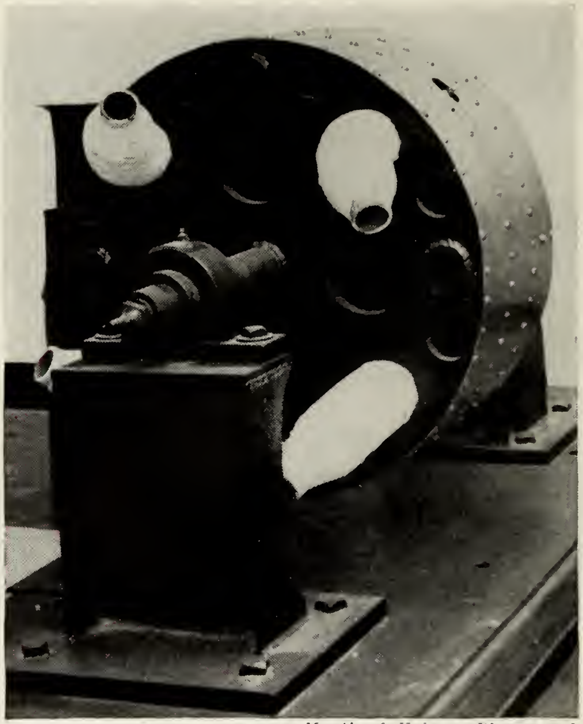
This $34,000,000 installation was authorized by Congress in 1940—nearly a year after the Germans had made the first successful jet-propelled flight.

One of the laboratory's prime objectives was to provide facilities for evaluating aircraft power plants under conditions where air density is but a third that at sea level, with temperatures ranging down to −48°F, and at speeds up to 500 mph. Such conditions had been simulated on a small scale in test rooms but never in a 500-mph airstream 20 ft in diameter.

Construction of such a tunnel was a bold venture, for extensive auxiliary facilities were required for refrigerating and evacuating the whole tunnel, as well as a system for continuously removing exhaust gas and supplying new air. The refrigerating unit, for example, is the world's largest low-temperature plant, with a capacity equivalent to 10,000 tons of ice

per day. Nowhere else in the world can jet engines be tested under such accurately controlled high-altitude flight conditions.

Rushed to completion and put in operation in December, 1943, the high-altitude tunnel immediately went to work—with NACA-developed instrumentation—on full-scale airplanes. By clipping the wings of a



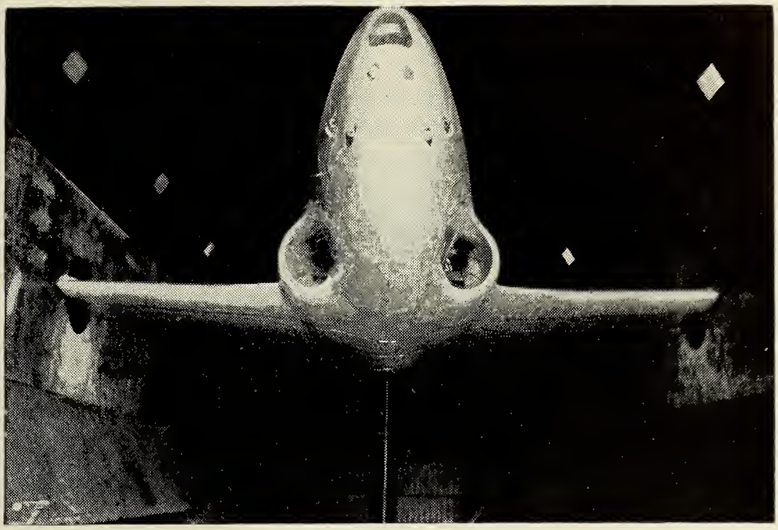
Martin & Kelman Photograph

Close-up of the NACA rotojet engine. This is one of the simpler jet applications and could develop into a useful and inexpensive power plant for smaller aircraft.

Bell P-59, it was possible to mount a complete plane in the test section, and the first detailed performance data of a turbojet unit under altitude conditions of forward flight were obtained. Soon afterward, a Lockheed P-80 with clipped wings went into the tunnel to determine the performance of its I-40 engine under actual altitude conditions.

NACA's reconversion from war to peacetime operations was quickly accomplished, for basic research is much the same whether the objective is to destroy or to create. Though a large part of its work will continue to be basic research for military aircraft, the other elements of air power

are not being neglected, for much of the work will be applicable to commercial transport planes; and many intriguing experiments are being conducted on jet-propulsion ideas directly concerned with tomorrow's personal planes.



Lockheed P-80 Shooting Star in NACA's high-altitude wind tunnel at the Engine Research Laboratory. This tunnel was the first in the world in which aircraft could be tested at high speeds at simulated high-altitude conditions. (*Courtesy of NACA.*)

But whatever the type of craft being worked on, the policy will be, as the Committee has stated

. . . to pursue its unceasing quest for knowledge in the science of aeronautics —a science destined to exert a profound influence on the future of civilization. Continued American leadership in aeronautical research and continued application of the results by the American aviation industry will do much to insure the military and economic security our nation has fought so hard to retain.

CHAPTER SEVEN

Tough Problems Still to Be Whipped

After the defeat of Germany, and with time rapidly running out on Japan, military restrictions, which had been quite rigid throughout the war on all aspects of jet propulsion except general principles of operation and external photos of the few Allied jet fighters that had taken to the air, were somewhat relaxed in the interests of acquainting a wider circle of professional engineers with the basic technical problems and more important trends and developments.

We have already referred to the big international gas-turbine conference at Swampscott, Mass., held under the auspices of the Army Air Forces and General Electric. During this conference, which was on a confidential level, Army, Navy, and British security officers reviewed certain technical papers and recommended their release for use at general engineering gatherings. From that time, regional and national meetings of the IAS, ASME, Society of Automotive Engineers (SAE), etc., were not regarded as complete without discussion of jet-propulsion and gas-turbine developments. Probably the top conferences in which these problems receive specialized attention are the aircraft-propulsion meetings held by the IAS during March of each year in Cleveland. In England, a full day's discussion on gas turbines was held by the RAS on Mar. 13, 1946, at the Institution of Civil Engineers (ICE). Sir Frederick Handley-Page was in the chair, the speakers including some of the engineers, such as Dr. Hooker of Rolls-Royce, Dr. Ricardo and Clarkson of de Havilland, and Carter of Gloster, who spearheaded British gas-turbine developments during World War II. Whittle, Banks, Halford, and many others took part in lively discussion after each paper. A considerable number of such technical papers, read on both sides of the Atlantic, will be found in the Bibliography.

In this chapter, a few special matters and also certain aspects of some of the unsolved problems in the field will be touched upon, based on these discussions or from similar sources.

Metals vs. Heat. A principle of physics is that the hotter the gases in the combustion chamber the more rapidly they expand, the more urgent is their desire to escape, and the faster they turn the turbine in their rush to get away. The faster the turbine turns the more power it produces.

Thus, the higher the temperature the greater the efficiency of the jet engine but, unfortunately, the greater the stress on the metals.

Metal experts have known for decades that the strength of steels drops sharply when heated above 1100°F. The aircraft gas turbine could not be efficient unless it worked at heats above 1200°, permitting the temperature of the gases after expansion to rise to 1250 to 1400°. This is the range in which today's British and American jet engines work; and in this range, up to 75 per cent of the power is needed to drive the compressor, the balance being available for useful work. Efficiency will be much higher when metals are developed that can handle gases with temperatures in the 1800 to 2000° range.

In this battle of the metals, the Germans had to offset their shortcomings in special steels by complicated but extremely ingenious design to provide the maximum lightness, strength, and efficiency possible with the low alloys available. The German jet-plane turbines were designed for only a relatively short life in service. The basic cause for this condition was the lack of strategic materials such as cobalt, molybdenum, nickel, and columbium, all of which Allied metallurgists regard as indispensable in producing high-temperature-steel alloys for gas turbines. At the end of the war, it became apparent that the Germans were on the track of entirely new developments which would have improved this situation—another indication that V-E day arrived not a moment too soon.

As we have seen (page 100), development of heat-resistant alloys for the very high temperatures required in supercharger buckets (1500 to 1600°) was the royal road to development of the aircraft gas turbine. These alloys are so hard and tough that they are difficult or impossible to machine, and hence a process to cast directly to size (a minimum airfoil-edge thickness of 0.010 to 0.020 in. is sometimes required) with a small amount of finish grinding appeared desirable.

One of the most convenient uses of the precision-casting process, developed by Haynes-Stellite Co., is for the prompt trial of new designs. The process is more rapid and less expensive, for a few hundred or thousand parts such as blades, than forging methods and lends itself to rapid changes in minor details of design. However, as development of the Whittle type of General Electric I-series of gas turbines proceeded, it was found that the elevated temperature-fatigue strength of fine-grained forgings was higher than that of the cast alloys with coarse grain. On the I-16, for example, castings of cobalt-chromium-molybdenum alloys failed on test in a fraction of the life of Hastelloy B nickel-molybdenum-iron alloy forgings which were adopted as standard.

In the early stages of the I-40 program, Hastelloy B forgings were specified and demonstrated to have a superior life over castings. However, the I-40 program skyrocketed at such a rate that forging facilities could not be built up and personnel trained fast enough to produce forged blades, and, consequently, castings were used almost entirely in production. The first I-40 units with cast blades were given a short-rated life; but with improved damping capacity, assembly techniques, and balance, castings on the I-40 at the present time approach the earlier test results with forged blades.

The Westinghouse jet engines with forged blades having a design incorporating high damping capacity were changed for high production to blades machined from bar stock for one design and to cast blades for a more advanced unit for production convenience and economy. No difference in life between cast and wrought blades has been reported from these turbine units.

Metals vs. Creep. To operate at proper efficiency, the turbine must spin so fast that the effect of centrifugal force on it is very great. When ordinary steel is cold, it can spin at a tremendous rate without rupture. But steel starts to weaken as temperature is increased. Thus, at room temperature, steel may have a tensile strength of 100,000 psi; but at 1200°F, it may decline to 30,000 psi; at 1600°, to 15,000 psi.

Since the start of their jet program in England, slow but steady progress was made in developing the heat-resistant metals required for British turbojet engines and propeller-turbines. Jessop's G.18B austenitic steel has been widely used for turbine disks and solid rotor forgings for axial-flow compressors. For the highly critical turbine blades, Henry Wiggin & Company's Nimonic 80 high-nickel gas-turbine-blading alloy has been found successful in Rolls-Royce, de Havilland, and other well-known aircraft gas turbines at a gas temperature up to 1500°F.

At the high temperatures at which the turbine must operate, the steel weakens in direct proportion to the increase in heat, and centrifugal force pulling at the blades elongates them, an action called "creep." At great speeds and temperatures, the blades eventually fail and damage the engines. To attain most efficient operation, the turbine in a jet engine may revolve as high as 12,000 to 14,000 times per minute. At today's 12,000- to 14,000-rpm speeds, the stress on each turbine blade amounts to several tons—a stress that must be borne by a blade that weighs but a few ounces and is hardly thicker than heavy wrapping paper.

But the turbine disk and blades are not the only units that must withstand extremely high temperatures. The turbine-nozzle diaphragm blades, for example, must retain their exact shape to direct the hot gases efficiently

against the revolving turbine blades. And even though the diaphragm is a stationary unit, the high temperatures involved require further development of alloys.

After years of grappling with the problem, metallurgists are inclined to eliminate steel as a base for high-temperature alloys for jet engines. The comparatively low-stress rupture temperature of iron renders it useless. None of the aircraft gas-turbine designs tested to date has utilized alloys containing more than 60 per cent iron in the turbine, buckets, nozzles, or case; and current models use materials containing less than 30 per cent iron in most cases. Those units now in the development stage use materials containing far less iron in their composition. Metallurgists are convinced that materials designed for operation at temperatures higher than 1500°F will contain no ferrous materials of any kind, with chromium, nickel, and cobalt beginning to replace them. Designs are now in the experimental stage with a 1700 to 1800°F range, which constitutes the maximum practically attainable at the present time. Ceramics have been suggested for turbine blades, and much research is now under way in this field, but results to date have not been especially promising. The low strength of ceramic materials presents problems in their application to the astonishingly high centrifugal stresses produced by the high-speed aircraft gas turbine.

As Dr. William R. Hawthorne of the British Air Commission, Washington (now on the faculty of MIT), told an SAE meeting:

> Research is needed in two main directions. In metallurgy, there is much yet to be achieved in developing materials to withstand creep and fatigue, oxidation and erosion, at ever higher stresses and temperatures. In aerodynamics, compressible flow is the greatest field of research. The control of gases moving at high speeds must be perfected. The aerodynamics of the combustion process must be better understood, and the knowledge applied. Workers on these problems have made possible the present achievements of the aircraft gas turbine. It is upon the success of their continued work that future progress depends.

FUELS FOR JET. Although aircraft gas turbines offer solid advantages over reciprocating engines in the matter of lightness, simplicity, freedom from vibration and icing, self-cooling, quietness, and ease of maintenance, one disadvantage at present is high fuel consumption because of poorer thermal efficiency. This, however, is expected to be overcome in the relatively near future. Although any fuel can be used that can be blown through a nozzle and will burn in air, all the big oil companies are working hard on the development of a special fuel for jets, and petroleum engineers insist that as yet we know practically nothing of the secrets

that lie locked up within crude petroleum. As Ben T. Salmon, Ryan Aeronautical Co. former chief engineer, reported to an IAS meeting:

> Given a liquid fuel of high energy content, gas-turbine designers will transform that chemical energy into mechanical motion which the aeronautical engineer will convert into more efficient and economical air transportation than any we have yet envisioned. Analyze, for example, what the effect would be upon the economics of some present-day airplane if a fuel releasing twice as much heat energy per pound as present fuel were available. Consider the possibilities on the basis of a given range, and determine the increase in ton-miles which could be hauled; or on the basis of a given pay load, imagine the advantage in terms of increased range.

Basically, all that a jet fuel needs is to have high heating value and be capable of being fed continuously to the combustion zone. Other characteristics are so desirable, however, as to be virtual necessities. The fuel must be free from solid abrasive particles that would erode the mechanism, a requisite both of the raw fuel and of the products of combustion. The presence of silica, for example, or of combined silicon that would burn in the flame to silica is a serious drawback to any fuel. Soot at high velocity is also harmful. Other elements yielding similarly abrasive oxides must be excluded. The fuel must remain liquid at the low temperatures encountered in flight at high altitudes. Easy flow at temperatures down to the required point of $-80°F$ is characteristic of gasoline and naphthas, but even some kerosenes become sluggish or actually congeal in this low-temperature range.

Also, a practical necessity for a jet fuel is a high flash point—the temperature at which the fuel is sufficiently volatile to form a combustible mixture with still air. The higher the flash point of a fuel, the safer it is to carry in a plane. The flash point of ordinary gasoline is below normal atmospheric temperatures, and thus its use involves at best a certain hazard of explosion which is particularly great in military planes. In a jet fuel, on the other hand, the flash point can be 105°F.

The criterion of a clean fuel that burns without considerable residue is easily met; but the combination of low volatility and, consequently, high flash point with an excessively low freezing point, is sometimes considerably more difficult to meet with practicable fuels. Either requirement alone would permit the use of immense volumes of petroleum products already available, but the combination of the two in a single fuel practically requires that it be especially refined for the purpose and thus places it among the special fuels.

Also essential to fuel efficiency in today's jet engines is its ability to burn in dilute mixtures with the large volumes of air used. Every com-

bustible substance requires a definite proportion of air for its complete burning, and it will burn in mixtures both more concentrated and more dilute than the ideal. The requirement of high dilution to keep temperatures down limits usable fuels to those capable of burning at dilutions necessary to meet temperature restrictions. This adds to the complexity of the fuel problem, but it still leaves a wide selection available to the engineer to power his future aircraft.

Perhaps the reason the jet-fuel problem still seems relatively simple is that we do not yet know enough about it. The first automobiles were powered by the waste naphthas of kerosene refiners, and it was only after decades of operation of millions of cars that efficiency and the factors affecting it became important. This may also be true of jet engines, and future developments may show the need for special qualities in their fuel now unsuspected in our present knowledge of the subject.

Research in the field proceeds at a swift pace because of its bearing on the rapid transition of both fighters and bombers of the Allied nations to all jet- and propeller-turbine-powered aircraft. Its significance in the development of long-range air transports for world travel and commerce is hardly less vital. Given time, the chemical industry's petroleum-refining division will certainly come up with the answer. But meanwhile it looks simple—probably much simpler than it really is.

MAINTENANCE PRINCIPLES. Because the gas-turbine jet-propulsion power plant is basically a very simple unit, its service and maintenance are, in some respects, much simpler than those required for reciprocating engines.

But because the jet engine is a mechanical device, it has its own peculiar causes of trouble that require specialized training to overcome. Its extremely high speeds—up to 15,000 rpm—and close tolerances demand that an unusual degree of care and cleanliness be maintained; and its principle of operation calls for new procedures. Both these factors mean that the work of the maintenance man is just as vital for efficient and economical operation as it has ever been, in either military or civil aviation.

Both centrifugal and axial-flow jet engines may be divided into five major components: the compressor and turbine, or rotor assembly; the compressor casing; combustion chambers; exhaust cone; and accessories. Each component naturally presents its own service and maintenance problems, but military secrecy still prevents a detailed discussion of specific American types.

The basic maintenance principles can, however, be discussed in general terms, as a means of pointing up what types of training and equipment

will be increasingly necessary as this type of power plant comes into more general use.

Disassembly procedures will, of course, vary according to manufacturers' instructions for each model, but American jet units appear to have been designed with some thought for facilitating the work of the maintenance man—something that can't be said for at least one German unit, the Junkers Jumo-004.

One of the most important features in overhauling the rotor unit is to ensure proper balance of both impeller and turbine. Since, in present designs, these components cannot be replaced during postoverhaul assembly as a complete unit, they must be assembled outside the engine, checked for runout, dynamically balanced, then again disassembled. Special balancing machines have already been made available, capable of showing unbalances of 4 to 6 g-in. for each 0.001 in. deflection.

To give an idea of the extent of work necessary, balancing procedure such as is necessary on turbosuperchargers or other high-speed rotors is outlined as follows: With the unit in the balancing machine, place a small piece of clay on the impeller between any two vanes near the periphery; run the rotor up through critical speed, and check maximum spread of indicator; stop the unit, and mark just below the clay the amount of unbalance. Then move the clay 90 deg in either direction, and repeat the process until four tests have been made. Starting with the lowest of the four readings, move the clay a short distance toward the next lowest reading; and, if the readings show improvement, continue moving the clay until the lowest possible reading is obtained. At this point, remove or add small amounts of clay as necessary to get the readings within the allowed tolerance.

This same process is repeated on the turbine, placing the clay just inside the turbine wheel's outer rim. Then metal equal in weight to the lump of clay must be removed from the opposite side of the unit. In the case of the impeller, this is hand-filed out of the periphery between impeller vanes; in the case of the turbine wheel, it is removed by a hand grinder from the balancing ring, which is just inside the turbine-wheel rim. In each instance, there are some limitations in both weight and location.

In the case of an axial-flow compressor, each individual disk would have to be balanced separately, then the unit as a whole checked to ensure proper balance.

There are, of course, vital detailed procedures, varying with different models of both axial and centrifugal types, that would add to or detract from the time necessary for such work; but the principles would remain

constant, and the necessity for extreme care and cleanliness throughout the job would remain equally important. Servicing and inspecting of bearings, for example, require at least the same care and precision as those essential for any other aircraft unit.

Clearances on jet engines, too, are extremely important and must be carefully watched. Impellers on centrifugal engines, for instance, must be meticulously adjusted for fore-and-aft clearances, sometimes with specially built tools. Turbine-nozzle shroud-ring clearances must be carefully maintained; even exhaust-cone clearances have to be kept within definite limits to make sure the engine will perform as it should when properly handled.

Combustion chambers, being peculiar to jet engines, require their own specialized type of inspection and maintenance. In most cases, daily inspection can be made without removing the engine from the plane. Such inspection consists of checking flame tubes or liners for excessive burning, warping, or cracking. This type of maintenance requires special training, because discoloration in the combustion-chamber assembly is not necessarily a true indication that liners are burned, since they can be beyond safe operating limits without discoloration showing on the outer unit.

On some engines, the normal inspection routine calls for removing only the lower combustion-chamber assemblies to inspect the liners and, depending on their condition, deciding if it is essential to replace all liners.

In routine inspections, the fuel manifold assembly must, however, be removed for inspection in prescribed sequence, then examined carefully for cracks, structural flaws, or other damage. And, as is the case with reciprocating engines, great care must constantly be exercised to make sure that no dirt is allowed to get into the fuel system.

Overhauling the fuel system requires (in addition to the disassembly, inspection, and repair) a reassembly outside the engine for testing to make certain that the entire unit functions properly. This includes, for example, two types of test: an idle-pressure test to ascertain that all fuel nozzles are performing properly; and a flow-balance test—which requires a flow-balance stand—to make sure that an equitable flow of fuel will reach all combustion chambers.

Typical of the care required in maintaining jet-propulsion engines is that which must be given the exhaust tail cone. Apparently only a simple structure slapped together of sheet metal, it must nevertheless be kept in good condition, for it is in this area that all the turbulence of the ex-

panding gas is converted into direct thrust. Thus, the shape of the inner as well as the outer sections must be kept to true dimensions; also, the clearances between turbine-bucket tips and shroud ring must be within tolerances to avoid reworking or discarding the cone. Thus, even though it is a lightweight and unglamorous structure, it can no more be tossed around than can close-fitting cowlings for reciprocating engines.

Gas-turbine jet-propulsion engines have one distinct economy and time advantage over conventional reciprocating engines in that they require far fewer accessories. One of America's best known types requires only the following attached accessories: starter motor, tachometer, starting and main fuel pumps, lubricating- and scavenge-oil pump, governor, barometric pressure valve to maintain constant speed regardless of altitude, and lubricating oil filter. The accessory case of the Junkers Jumo-004, as another example, provides only seven outlets, at least one of which was found blanked off on several engines studied.

Moreover, these accessories are very similar to those employed on today's reciprocating engines, so maintenance personnel who understand the current units should have no difficulty taking proper care of those on jet engines. It is largely a matter of maintaining the same degree of precision and care that has always been fundamental to good maintenance.

It is patent that any shop undertaking jet-engine service and overhaul will have to meet, if not actually excel, the high standards of cleanliness associated with today's successful overhaul base; for if cleanliness is next to godliness in the reciprocating-engine shop, it's practically the same thing as godliness in the jet-engine shop.

Not only is this quality essential to maximum performance and life of the power plant, but it also serves to reveal damage that can imperil the whole unit. As a case in point, since jet engines generate terrific heat, any superfluous oil or grease must be kept away because, in addition to interfering with radiation of the heat, it creates a fire hazard. Even selection of lint-free cloth for cleaning is essential, both for the high-precision parts and for the small metering orifices in the fuel system.

Because of the basic simplicity of the gas-turbine jet-propulsion engine, it should, as its design progresses to the point where it becomes a competitive factor in peacetime aviation, show lower maintenance costs than the complicated reciprocating engine. Trouble shooting, although requiring a high degree of skill, should be an easier and faster job simply because there are fewer sources of trouble to track down.

Today's overhaul consists primarily of tear-down and replacement of parts; nevertheless, the ingenuity of maintenance men is considered almost

certain to reduce costs further by reworking, adapting, and continued use of the old reliable preventive maintenance. One thing is certain, though, and that is that highly skilled and ingenious maintenance will always be just as important to successful jet operation as it always has been with any other type of power plant.

CHAPTER EIGHT

New Horizons for Flight—A Glimpse of the Future

ONE DAY IN dim antiquity, a cave man stumbled and fell because he stepped on a short piece of log. While licking his wounds, he reflected sluggishly upon his experience. Slowly it dawned upon his overtaxed mentality that he had landed quite a distance from the place where he began to fall. The log, too, had rolled along with him.

It took a long time for him to profit by his adversity. Through the long Neanderthal nights, he groped in his little mind for an explanation. Then came the day when he killed a bear so big that he was unable to drag it home. The two experiences became related, and a flash of inspiration came upon him. Eagerly he sought the short log, and he used it as a roller to push and pull the bear to his cave.

The social and economic implications of this technological discovery were enormous. No longer did this ancestor of Archimedes have to share his kill with those who helped him drag it home. He had found a way to live more easily and independent of his fellow men. He had founded the science of mechanics and initiated the basic development of the wheel. The research program that he started is still going on. In one form or another, it will always be with us.

Centuries passed before some Sumerian sliced a log into disks and mounted them on axles. Then came the cart and chariot, depending first on men, then horses, for their motive power. Even today, our modern automotive engineers are still obsessed by the idea that the engine should be in front. More centuries passed before men found ways to turn the wheel sidewise, carve out blades, and use it as a propeller, fan, or turbine.

Through all these centuries, man devoted most of his ingenuity to things that rotate. So powerful was the fascination of the wheel that engineers abhorred the sliding things. Translation was avoided wherever possible. Great industries grew up around the idea of avoiding friction where sliding motion was unavoidable. Then man succeeded in defying gravity and emancipated himself from the surface of the earth.

With this new freedom came emancipation from the spell cast over us by that ancient ancestor who stumbled on the log. It would be folly

to contend that the age of rotation is at an end. But it would be equally fallacious to deny that the age of translation has begun. The wheel will be with us while civilization lasts. So will its many variations. The fundamental motion of the earth will be imparted to everything that operates on the earth's surface. But as we learn to leave our planetary home, translation by reaction will furnish the primary motive power for our vehicles.

Reaction engines do not supplant any of the general classes of power plant that we now possess. Neither do they spell doom for air propellers. They simply fill in a new area of the propulsion spectrum. They represent continuation of man's progress in movement above the substratosphere and beyond the neighborhood of the speed of sound.

The airplane was almost the first true vehicle of translation, but its forward motion depended upon the rotation of its airscrew. The propeller came as a natural consequence of its great success and high efficiency in marine design. And the very first air propellers were remarkably efficient in themselves.

It was not metallurgy alone that retarded the application of jet propulsion and led sound engineers to scoff at rockets. It was primarily the cold, hard fact that man had not found ways to move fast enough to reach the range of efficiency of reaction engines. That range begins around the area of the speed of sound. German scientists set 400 mph as the minimum air speed for jet-propulsion aircraft long before they had planes capable of that speed. They began jet research in the middle thirties but delayed its application until such planes were available.

Even at 400 mph, the jet type of engine is not at its best. It begins to be useful when its forward speed equals the rearward velocity of the jet. The problem of jet designers is basically one of producing a jet slow enough to equal the speed of the plane in which it is installed. That is why jets produced by rockets are not yet practicable for continuous flight. Their speed begins at about 800 mph, which is a little above the speed of sound.

Jet engines therefore find themselves awaiting airplanes in which they can be installed for best efficiency. Such airplanes are on the way but have not yet arrived. Between them and the present planes there is a hurdle called "compressibility," now the chief limiting factor in increasing speeds of flight.

Compressibility may be best explained by the analogy of the snow plow. Its blades moving through a drift could reach a speed where snow packed ahead of them would impede the progress of the plow. Air passing over a wing at sonic speeds also tends to pack. It does not impede

the movement of the wing, but it does build up detrimental shock waves. Those waves destroy the smooth flow of air around the wing. The breakdown of this so-called "laminar flow" destroys the lifting power of the wing and sets up serious vibrations in the structure. If speed is increased beyond that of sound, no further aerodynamic difficulty is experienced.

Aerodynamicists throughout the world have been striving to overcome this hurdle. Much progress has been made. As early as 1936, the Germans had many laboratories devoted to the study of subsonic, transonic, and supersonic speeds.

Our NACA has supersonic laboratory equipment at Langley Field, Va., and Sunnyvale, Calif.

One possible solution seems to lie in developing a wing so thin that compressibility comes late with increasing speed and with less violence. This avenue of research leads to metallurgy and structural engineering because it requires great strength without space for internal bracing. During World War II, much progress was made in the development of stronger aluminum alloys. Still stronger ones are on the horizon.

Another course lies in new means to control the layer of air closest to the moving wing. Various suction devices have been tried to make the air cling more closely during the shock-wave range. These and other programs of research are under way, and promising results have been achieved.

Time, money, and thoughtfully directed work will solve these problems. Then a whole new era of high-speed transportation will open out before us. It may easily carry us far beyond the confines of our little world, for the jet type of engine does not need sea-level air pressure to operate. In fact, it runs as well or better in the rarefied air of higher altitudes.

It will be at these high altitudes that the first attempt will be made by a man-carrying plane to conquer compressibility. The Bell XS-1 is the first of a long line of flying laboratories developed to pass into and perhaps beyond the critical transonic speed range. As this is written, the world speed record for an inhabited aircraft stands a little above 650 mph. Between 600 and 900 mph lies that great barrier of transonic flight. More than a decade of aerodynamic research by NACA has told us many of the things that will happen to an aircraft traversing that barrier. Our engineers know more about these violent reactions than do the scientists of any other nation. The XS-1 has been developed by Bell engineers on the basis of these data. The AAF has acted as the procurement and evaluating agency in this project.

The untimely and ironical death of Bell's chief test pilot, Jack Woolams, in a plane developed for participation in the 1946 national air races

delayed the XS-1 project a few weeks. Pilot Woolams had been assigned to the transonic flights. But in December, 1946, Chalmers (Slick) Goodlin descended in the miniature elevator built into the special B-29 bomber that carried the XS-1 to its initial 27,000 ft, climbed through a small door, and seated himself among the myriad of instruments and recorders. After checking his controls, he cast the plane loose from the mother ship and started the 6,000-hp rocket motor of the XS-1. The 210-lb Reaction Motors N1500 C4 engine was used for only a few seconds, and the speed attained was 550 mph. Many other test flights will follow, and eventually the XS-1 is expected to go through and beyond the transonic speed range to a possible 1,700 mph. In the meantime the Douglas Skystreak has broken the international speed record twice within a few days (640.7 mph on Aug. 20, 1947, and 650.6 on Aug. 25).

And so we find mankind on the threshold of new transportation progress. But what is the immediate future of jet propulsion?

In the field of military aviation, the era of jet propulsion is already here. Most of our new high-speed fighters and pilotless aircraft are already in this category. As of Jan. 1, 1947, the AAF had 22 jet fighters and bombers under development, and the Navy had 13 more. Britain had at least another dozen. Because it is necessary for these planes to reach the ideal speed and altitude for jet propulsion with greater efficiency, the combination of jet-and-propeller- or jet-and-rocket-assisted take-off will be indicated in many bomber designs of the future. Pure jets will be confined to fighters, probably with centrifugal-flow types for single-jet fighters and axial-flow types for twin-jet models, as a general rule.

When compressibility problems are solved, the limiting factor in the speeds of inhabited planes will be physiological. Here speed is not the problem, but the acceleration experienced by human bodies can have devastating results. It must be remembered that turning at high speeds is angular acceleration and causes a pilot to black-out just as he does in linear acceleration or deceleration. The old idea of placing pilots in a prone position will be revived. This plan was advanced to keep the blood from rushing away from the head, which is the chief cause of black-out. Medical science will contribute to the solution of this problem when it is found. Until then, the higher speed aircraft will be guided missiles flown without pilots and remotely controlled. The drones that flew through the atomic cloud at Bikini, with their radio control unaffected by intense radioactivity, bear witness to our rapid progress in the development of guided missiles.

Rapid advances were made during World War II in the development of pilotless aircraft. In Germany, guided missiles came just a little too late to cause us serious setbacks. Now we have progressed far beyond them. And this type of aircraft is the logical carrier of atomic bombs.

High-speed, jet-propelled, guided missiles carrying atomic bombs would not be exactly conducive to the continuance of civilization. Yet there are practically no major technological problems standing in the way. Our experience with target-seeking missiles indicates that this feature could be added easily to the combination. Television and other devices will contribute to the accuracy and effectiveness of such weapons, which would probably be powered by pure jet engines without propellers.

Atomic power plants for aircraft are still a long way off, but work is being done in their development. Chief obstacle is the weight of the material needed to protect pilots from radioactivity. When these engines come, it is reasonable to assume that they will first be used in guided missiles, where pilot protection is unnecessary. Their launching equipment could be shielded for ground personnel protection, and the launching accomplished by remote control. The effect of radioactivity on the electronic devices used within the missile for control is still undetermined, but it might easily be detrimental. And yet the development of some lighter shield against radioactivity could accelerate atomic power plants tremendously.

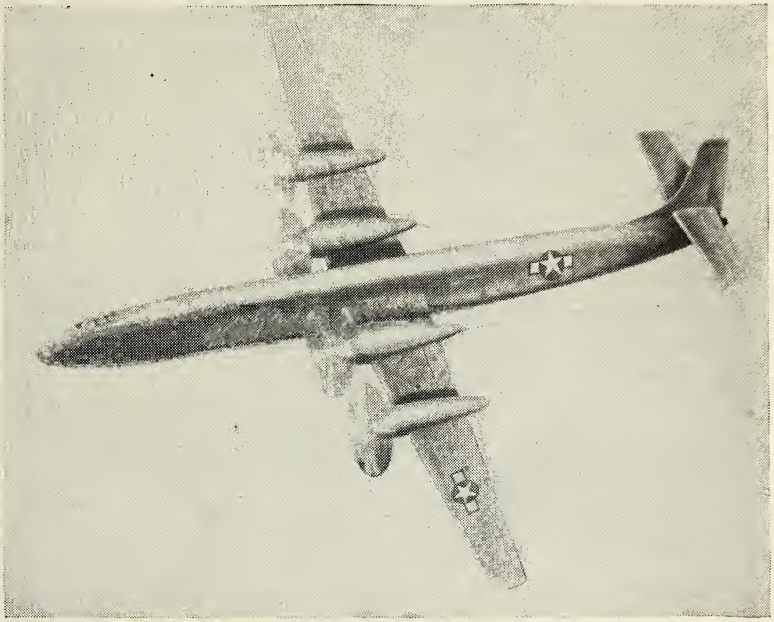
Large bombers and military and commercial transport planes will soon begin to appear with jet-propulsion power plants. When power units above approximately 2,000 hp are required, the gas-turbine engine because of its simplicity and lightness begins to be attractive. When 4,000- to 5,000-hp units are indicated, the gas turbine begins to be imperative. It is doubtful that reciprocating engines above this power rating will be developed.

After a reciprocating engine grows beyond 1,000 hp, it becomes virtually a multiple of a smaller design. We have just about reached the peak of power output from an individual cylinder, which is less than 175 hp. Recent large engines have been ingenious devices to add more cylinders and pistons to a single crankshaft. The increasing mechanical complications of such linkages have reached the point where each new row of cylinders added introduces far greater problems for the designer.

None of this is true of the gas-turbine engine. It thrives on enlargement. Much of the ingenuity in its design has been expended in trying to make it operate in small units.

A tough problem has been that of streamlining engines into aircraft wings or fuselages. Engine designers have collaborated by striving to

keep down the frontal area of the power plant. Reciprocating engines have grown longer instead of fatter. This means more rows of cylinders and more cooling problems. Much brilliant work has gone into the development of cooling and cowling of these engines. But, in spite of it all, more and more power and aerodynamic efficiency are being wasted in cooling as engines grow larger.



This bomber design, projected by the AAF, has one propjet engine in the nose and one pure jet in the rear of each of four nacelles. The nose engines and propellers would be used to reach ideal speeds and altitudes for the pure jet engines at which stage they would go into action. (*Courtesy of Cornell Aeronautical Laboratory.*)

The gas turbine lends itself to increased length rather than diameter. Compressor stages may be added axially almost indefinitely. Cooling is still a major problem in the gas turbine. High temperatures shorten the life of some of the parts. In German designs, a considerable quantity of power was wasted in cooling. Part of this difficulty lay in lack of scarce materials.

Already we have made great advances in lengthening the life of gas-turbine parts. Daily progress is occurring in the metallurgy of high-temperature alloys, and research in ceramic materials is going forward. Fabrication of parts like turbine blades from the new metals also presents

new problems. High hopes are held for application of the "lost wax-casting process" attributed to Benvenuto Cellini, lost through the intervening years, and recently revived. The problem of thermal shock, resulting from quick and violent temperature changes, has plagued the workers creating new ceramic materials. But any increase in the allowable operating temperature of a turbine engine above the current level of 1500°F is well worth the work it costs, because it pays off handsomely in increased power output and efficiency.

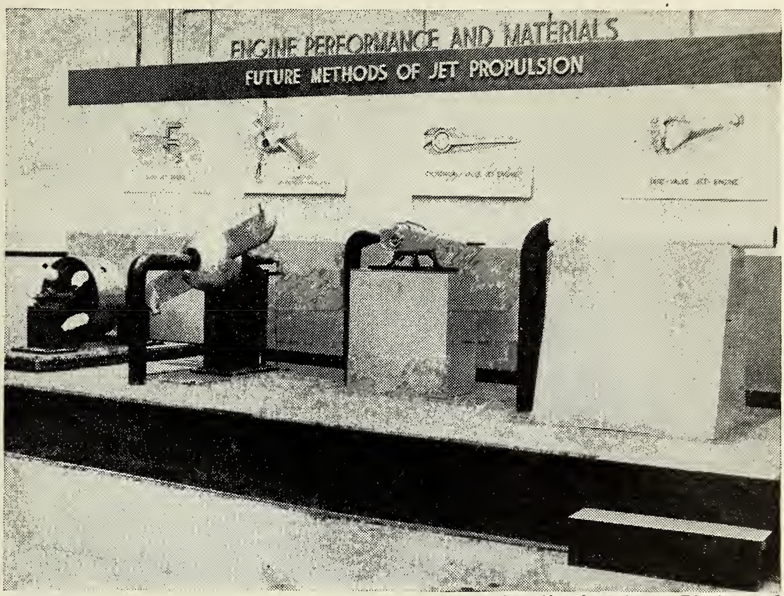
Another source of increased efficiency is the compressor element in the system. Since the over-all efficiency of the engine is the product of the efficiency of the turbine and the compressor, an increase in either element pays highly desirable dividends. Remarkable progress in compressor efficiency has been obtained by British advocates of the centrifugal type. A single-stage supersonic compressor of the axial-flow type, developed in the NACA laboratories, has an output that is the equivalent of several stages of current axial-flow types. These are but typical of many other projects under development in company and government laboratories. In fact, so much original research and development are now going on, that the shape of things to come is difficult to predict.

It is probably more realistic to look upon the gas turbine as a basic principle which will have many different applications. Just as we now have air-cooled radial and liquid-cooled in-line reciprocating engines, so we shall have centrifugal- and axial-flow gas turbines, each in the installation to which it is best suited; also units in which both types are combined.

Just as erroneous is the idea of the gas turbine as distinct from the reciprocating engine, because there is strong promise for a hybrid type combining both basic principles. Much engineering thought is now being given to the so-called "compound engine," which combines both fundamental types. Whether the result will be a big reciprocating engine compounded with a turbine or a big turbine to which is appended a small reciprocating engine is not yet clear. The advantages of compounding are well set forth in a RAS paper by Dr. H. R. Ricardo and an article in *Aviation,* November, 1946, by W. O. Meckley and L. J. Fischer of General Electric. Rather remarkable increases in the output of a large reciprocating engine have been obtained by Pratt & Whitney engineers, who have added an exhaust-driven turbine feeding-back power to the crankshaft. Wright Aeronautical has a promising power recovery project.

There is no doubt about the future of the gas-turbine principle and its revolutionary effects on transportation in the air and even on the surface of the earth. The big questions and the unanswerable ones are when it

will come to pass and what form the new power plant will take. We may hazard an answer to each of these. Five years will see great changes in power-plant design resulting from the influence of the gas-turbine principle. Large reciprocating engines will still be with us, but they will be different and more efficient. They still hold the advantages for extremely long range, nonstop operations, military or commercial. An example is



Martin & Kelman Photograph

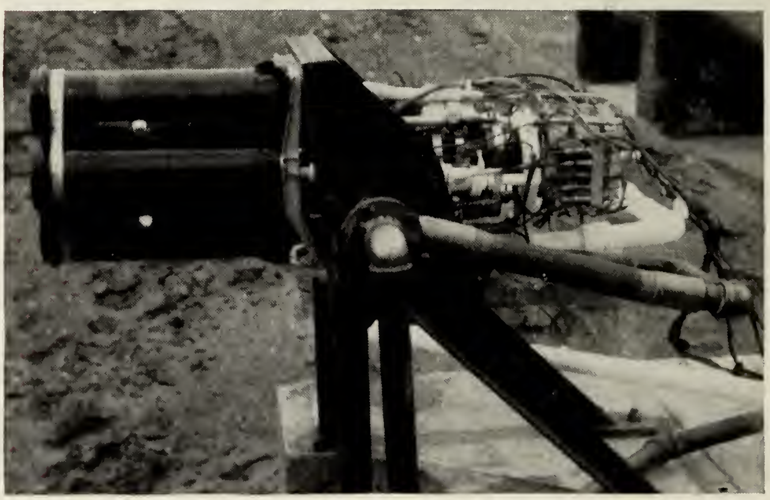
Future applications of jet propulsion. *Left to right:* rotojet engine, jet-propeller installation; cylindrical-valve engine, disk-valve engine. These and many other types are under test at the Cleveland Engine Laboratories of the NACA.

the Lycoming X-7755 36-cylinder, 5,000-hp engine. Smaller reciprocating engines may be with us longer than the larger types. Propellers are still and probably always will be useful, even though they are geared to gas-turbine shafts. New and remarkable progress in propeller design will enhance the airscrew's lease on life. Perhaps some day rockets or other means of assisted take-off will invade the speed range in which the propeller is now supreme.

It is unlikely that one type of gas-turbine engine will emerge and dominate the field. Planes have too many different jobs to do. They must perform all the functions of the many surface vehicles in the medium of the third dimension and some additional ones. Spaced in the spectrum for all known types of gas turbine will be combinations of these types; com-

U.S. Army Air Forces Photograph

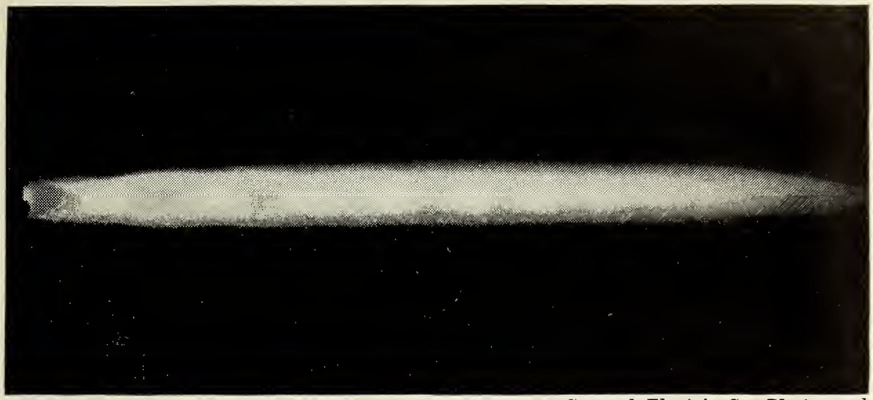
A P-51 Mustang fighter plane with ramjet engines on each wing tip. The ramjet is the ultimate in simplicity, being literally like a stovepipe with a fire in it. Compression is obtained by the ram effect of high-speed forward motion. This type of engine requires a speed of approximately 350 mph before it becomes operative, so the North American P-51 constitutes a flying test stand for the engine.



About the size and weight of a large outboard marine motor, the Reaction Motors N1500C4 four-tube rocket engine develops 6,000 lb of thrust for a total weight of only 210 lb. This is the power plant of the Bell experimental supersonic airplane XS-1. (*Courtesy of Aviation.*)

pounded engines; and, for a long time, piston engines. And there will be new varieties as yet unborn. Nor can we forget the crude athodyd and ramjet. They are members of the family who will soon be heard from.

The rocket that spurns the natural oxygen in the air and carries its own supply of the materials of combustion will play its role. Right now, it has important military value, but it looks a little limited for commercial use. However, the economic value of assisted take-off to commercial operators has not been fully explored. A rocket gentle enough



General Electric Co. Photograph

Jet speeds are difficult to measure. The Germans devised a spectographic method which enabled them to calculate the velocity from the angle of the reflected waves, or "diamonds," which can be seen in this photograph of a jet produced by a rocket motor.

to accelerate passenger planes yet sufficiently powerful to permit take-off with an overload of as little as 20 per cent or even less would alter the economics of air transport. It would contribute greatly to the constant efforts to give better service for lower fares. And even a less gentle rocket assist could provide remarkable aid to those operators who are seeking to close the gap between air- and rail-express rates per ton-mile. The rocket could boost the air-freight business beyond the fondest dreams of those who feel that air cargo will grow gradually.

The economics of operation of turbine-powered aircraft is too detailed even at this early stage of the scope of this volume. Those who would pursue this important phase more thoroughly should start by reading the competent analysis of S. P. Puffer and J. S. Alford of General Electric, whose paper touching on the subject is listed in our Bibliography.[1] Their conclusions will, of course, change as more efficient turbine power plants

[1] The Gas Turbine in Aviation—Its Past and Future.

are developed, but even now there are attractive applications in commercial aviation.

A few hints are all that can be given at this time, but they may whet the appetite for some of the things that lie ahead. During the last half of 1946, for example, some jet-transport experience was gained with the Nene-Lancastrian, with two Nenes outboard and two Merlins inboard. Passengers testified that the turbines were far smoother and quieter than the piston engines. On the two Nenes alone, cruising speed was 260 mph at 10,000 ft, and 330 mph with all four engines. Britain's immediate postwar plans were quite complete. A definite program was charted for the British aircraft industry by the Brabazon Committee, which issued specifications for a wide variety of commercial designs, popularly known as "Brabazon types" (the Bristol 167 became the Brabazon I). Britain regarded the 1947-1950 era as a transition period during which American equipment such as the Constellation and Stratocruiser will be used for the transatlantic runs, their own medium-weight transports for the shorter ranges, and the first crop of new designs for turboprops and pure jets brought to the operating stage. These latter include gas-turbine adaptations of such present models as the Handley-Page Hermes V (63 passengers), with four Bristol Theseus turboprops; the Miles Marathon 18-seater, with two Armstrong-Siddeley Mamba turboprops (of which 25 have been ordered for British European Airways); the Vickers Viking V.C.1, with two Nene I turbojets; and the Tudor VIII, with four Nenes. New designs to be tried out in this period include the ambitious 145-ton Bristol 167, first prototype of which will have eight Centaurus piston engines (2,500 hp each) and the second powered with eight Bristol Proteus turboprops of about 3,500 shp each. Other new designs include the Vickers Viscount (successor to the Viking) and a new de Havilland design (106) to be powered by four Ghost turbojets.

The 1951-1954 period is expected to see some of these aircraft in widespread service as the first stage of a predominantly gas-turbine era, with the emphasis on turboprops. New designs using turbojets will be developed during this time; and in the 1955-1957 second stage, many of them will supplant those using turboprops. Flight at 35,000 to 40,000 ft with pressurized cabins and at speeds of 500 to 600 mph are expected for the longer runs. This completes a 10-year forecast. Beyond that is anybody's guess.

In the United States, the 1947-1950 period shapes up something like this: During 1947, the 300-mph Constellation and Douglas DC-6 will be in widespread use and the first of the 350-mph Boeing Stratocruisers,

which will be used internationally, beginning in 1948. This will give our domestic and international airlines valuable experience in higher speed passenger traffic. By 1951, the first of the turboprop airliners in the 425- to 450-mph bracket may be ready for trial. A good many problems remain to be solved, but plenty of sound work is going on. The Martin 304 for United Air Lines and the Consolidated Vultee Model 240 are two transports for which turboprops have been scheduled. In the pure jet-transport field, American Airlines has shown an interest in the Rolls-Royce Nene, chairman C. R. Smith having stated that as soon as this or a similar turbojet reaches a stage of 500 hr between overhauls, America will be interested in a high-speed, high-altitude airliner designed around four of them. This would mean at least 500 mph at 35,000 ft or higher, and such an airliner could be ready for service tests shortly after 1952. More powerful American turbojets and turboprops now in the development stage may be ready within the next 2 years for new aircraft. A special version of the Boeing 377 Stratocruiser is expected to be fitted with two turboprops (outboard) and two Wasp Majors (inboard) within the next couple of years. Transport versions of some of the jet-powered AAF bombers should also be ready in the early 1950's. Air-frame configurations will include tailless designs with swept-back wings and flying wings, embodying boundary-layer control and other devices to increase efficiency as the transonic range is approached. In the more distant future, ramjets, rockets, and even atomic-powered aircraft will come into the picture.

As this volume passes through the processes of production and publication, new progress will be made in the penetration of the gas-turbine frontier. New masses of detail will be added to the many branches of development treated generally here. Our hope is that each one of these ramifications will form the basis for future volumes in the literature of the gas-turbine principle.

In this and in the related fields of aviation development, history has proved that we can rely completely upon the contributions of our scientists and technicians. But the cost in money of research and development in these new fields is rising far above the level of earlier work. The cost of high-speed research, for example, is paralleled only by that of studies in nuclear physics. Under the impetus of war and motivated by self-preservation, the American people never hesitated for a moment to accept this burden. In the softer era of uncertain peace, we are showing signs of indifference while nations nearer bankruptcy than ourselves appear to realize the importance of the work far more than we do. We can main-

tain our present lead only as long as we accept the burden and support the government-military-industry teamwork that has proved so effective in the past. If this volume can convince its readers of the importance of maintaining the lead, not only for military security but for fuller enjoyment of that security, it will have served its purpose.

Chronology of Aircraft Gas-turbine Developments

1917	The late Dr. Sanford A. Moss, General Electric engineer-scientist, explores the Frenchman Rateau's turbosupercharger experiments.
1918 *Aug.*	The Moss turbosupercharger is tested with highly satisfactory results on top of Pikes Peak on a 350-hp Liberty engine.
1919 *Sept.*	Using the Moss turbosupercharger, Maj. R. W. (Shorty) Schroeder flies to 18,000 ft; 6 months later, to beyond 33,000 ft.
1922	Edgar Buckingham's study and report on jet propulsion for aircraft (unfavorable at that time); later published by NACA.
	Development—continuing through 1937—of various heat-resistant alloys which progressively improved the efficiency of the turbosupercharger and prepared the way for the aircraft gas turbine.
1923	Buckingham NACA report indicates jet propulsion impractical at speeds then envisioned—250 mph.
1926	Dr. A. A. Griffith (RAE) advances theory of turbine design based on flow past airfoils. Experiments (with BAM and ARC sanction) begun 1927.
1928	Flight Cadet Frank Whittle presents RAF thesis on possibilities of jet propulsion and gas turbines.
1929 *Nov.*	Dr. Griffith suggests an internal-combustion turbine driving a propeller based on the contrarotating, contraflow principle.
1930 *Jan.*	Whittle patents design based on the principle of using a gas turbine for jet propulsion.
	Dr. Stewart Way, Westinghouse, starts design studies for turbojet and athodyd.
	Preliminary research in gas-turbine compressors is begun by Professor Prandtl of Junkers.
1935	Dr. von Chain of the Heinkel Company, Rostock, takes out basic patents on aircraft gas turbines (as Max Hahn).
1936 *Mar.*	Formation of Power Jets, Ltd., to develop Whittle's turbojet with centrifugal compressor.
July	RAE begins development of eight-stage axial-flow compressor Anne.

1937 *Mar.* H. Constant (RAE) presents plan for axial-flow turbine for propeller drive. Designated B.10; built by Metropolitan-Vickers in 1938-1939; and test-run October, 1940.

1937 *to* 1938 First three versions of Whittle experimental engine tested.

1938 Five-year program for development of gas turbines for jet propulsion initiated at Wright Field, resulting in preliminary contracts to General Electric and Allis-Chalmers.

Eastman Jacobs and Eugene M. Wasielewski of NACA begin axial-flow studies; build compressor to test theories.

RAE designs turbocompressor based on Griffiths' 1929 scheme. Built by Armstrong-Siddeley, 1938-1939, and tested in 1940.

1938 *to* 1939 C. A. Parsons organization develops eight-stage axial compressor Alice.

1939 NACA starts studies aimed at developing 500-mph turbojet.

Eastman Jacobs heads development of NACA "jeep" (engine-compressor-jet combination) at Langley Field.

Feb. H. Schelp of the German Air Ministry (RIM) placed contracts with Junkers for Ju-004 and Bavarian Motor Works for the BMW-003.

July Contract to Power Jets for Whittle flight engine W1 (to be built by British Thomson-Houston), and to Gloster Aircraft for experimental airplane E28/39.

Aug. Heinkel He S 3 flight-tested in flying test bed He-178, earliest aircraft to fly powered by a turbojet unit.

Oct. Development of He S 8 for the He-280 experimental twin-jet fighter begins at Hirth factory, Stuttgart.

1940 (*early*) Centrifugal supercharger compressor studies start at NACA; results very important in jet-propulsion development, since means for measuring compressor efficiency were developed. Congress authorizes funds for establishment of NACA engine research laboratory, Cleveland.

Apr. Rover Company begins development of Power Jets W2 engine, leading to W2B23 (prototype of Rolls-Royce Welland) and W2B26 (prototype of Derwent).

June Special report to Navy on the aircraft gas turbine prepared by the National Academy of Science.

July Metropolitan-Vickers begin development of F2 engine with nine-stage axial-flow compressor; bench-tested in December, 1941.

Aug. Italian Caproni-Campini CC2, with radial engine, axial compressor, and jet, flew Aug. 27, 1940, widely publicized as earliest flight of a jet-propelled aircraft.

Oct. Navy starts gas-turbine research work through Bureau of Ships.

Dec. Jumo-004 bench-tested. Flight-tested in modified Me-110 a year later, several months after flight test of Whittle unit in Gloster E28/39.

W1X engine assembled by Power Jets and test-run. Used for taxiing runs in Gloster E28/39, April, 1941.

1941 (*early*) BMW-003 test-run, unsatisfactory, with very low thrust. Compressor redesigned, other faults corrected in 003A.

(*later*) RLM supplies Heinkel with design of the Heinkel-Hirth 011. Development slow, bench test being reached in 1944; not flight-tested before end of hostilities.

1941 John K. Northrop presents turbojet proposal to Navy, gets go-ahead. Navy contracts with Turbo Engineering Corp. for complete design study. Pratt & Whitney inaugurates turbojet research under L. S. Hobbs; Allis-Chalmers brought into program.

Mar. General H. H. Arnold, chief of U.S. AAF, calls for progress report on jet propulsion before leaving for England.

Apr. NACA recalls Dr. William C. Durand from retirement to head up research projects on gas turbines and jet propulsion.

Whittle W1 engine undergoes 25-hr bench test to clear for flight test.

Major Frank Halford, after consultation work with Rover on Whittle gas turbines, begins design of H-1 in association with de Havilland.

Dr. Durand heads special committee to coordinate U.S. jet-propulsion program.

May General Arnold observes Whittle-Gloster and other British developments in aircraft gas turbines.

W1 engine, developed by Power Jets, built by British Thomson-Houston, flight-tested in Gloster E28/39, Flight Lt. P. E. G. Sayer at controls. Marks first flight of an aircraft powered by turbojet engine of successful type.

June Rolls-Royce sets up Derby test plant for centrifugal compressors.

July Secret conference of NACA's Durand committee with Army, Navy, and industry representatives to lay out American program. Axial-flow turbojet assigned to Westinghouse (19B) and axial-flow propjet to General Electric (TG-100).

Westinghouse completes athodyd study.

Aug.	Westinghouse completes turbojet study.
Sept.	Secret conferences in General Arnold's office with key representatives of AAF, General Electric, and Bell Aircraft; contracts to GE for Whittle-type gas turbines and to Bell for experimental jet fighter.
Oct.	Major Donald Keirn returns from England with W1X jet engine, drawings of W2B, and team of Power Jets engineers.
Nov.	First meeting of British gas-turbine collaboration committee, Dr. H. Roxbee Cox, chairman.
Dec.	Westinghouse engineers review program in light of Pearl Harbor, send W. F. Boyle to Washington; he returns with letter of intent for turbojet development.
1942 *Jan.*	Navy starts metallurgical studies as part of Westinghouse and Allis-Chalmers contracts.
Mar.	General Electric Whittle-type I-A unit makes test run (centrifugal compressor).
	Bell XP-59A jet-fighter prototype completed.
	Rover B26 (prototype of Derwent, featuring through-flow) test-run.
Apr.	De Havilland H-1 test-run.
May	Wing Commander Frank Whittle arrives in Boston with drawings of W2/500 turbojet engine.
July	Rover B23 (prototype of Welland) used for taxiing trials in Meteor.
	Navy completes preliminary tests on combustion.
	Jumo-004B test-flown in Me-262, first jet-propelled combat aircraft to take to the air, operational in Luftwaffe fighter squadrons 2 years later.
Sept.	Power Jets W2/500 test-run.
	First drawings on Westinghouse 19A completed.
Oct.	Navy combustion report, with military applications, completed.
	Bell XP-59A, powered by two General Electric I-A turbojets, officially test-flown at Muroc Lake, Calif., with Bell test pilot Robert Stanley at controls.
Dec.	Rolls-Royce WR1 (version of original W1) test-run.
1943 *Mar.*	De Havilland H-1 flight-tested in Meteor II.
	Westinghouse 19A makes first test-run.
Apr.	Rolls-Royce takes over work of Rover Company in production of jet engines for Meteor. Improved version of W2B23 Welland passes

	100-hr test. Design of W2B37 Derwent begins (based on Rover B/26).
Apr.	Armstrong-Siddeley tests ASX, 14-stage axial-flow compressor, two-stage turbine.
	General Electric I-16 turbojet test-run.
May	General Electric I-40 (J-33) and axial-flow TG-180 (J-35) projects begin at request of Matériel Command, Wright Field (now AMC).
	General Electric axial-flow TG-100 (T-31) propeller gas turbine test-run.
June	Gloster Meteor flown with W2B turbojet.
July	Rolls-Royce Derwent I (B/37) test-run, 8 weeks after start of project.
	Halford-designed de Havilland H-1 aircraft gas turbine (centrifugal compressor, through-flow) given by Wright Field to Lockheed with request for design of XP-80 experimental jet fighter.
	Westinghouse 19A completes 100-hr test.
	Navy combustion-research program starts at Bureau of Standards.
July to Aug.	Bell P-59A, powered by GE I-16 (J-31) turbojets, given extensive flight tests.
1943 *July (to* 1945 *Mar.)*	Following experimental jet-fighter projects initiated: Northrop XP-79 and McDonnell XP-85 (Westinghouse 19B), Consolidated Vultee XP-81 (GE T-31 in nose, J-33 in tail), Bell XP-83 (2 J-33's), Republic XP-84, and North American XP-86 (J-35).
1943 *Aug.*	Colonel Donald Keirn, AAF, and Captain Pearson, USN, lead gas-turbine mission to Britain.
	First test run of Metropolitan-Vickers F/3 unit with ducted-fan thrust augmenter.
Sept.	Bell P-59A arrives in England for testing of aircraft and turbojet by RAF. Test-flown at Moreton Valence airdrome by Bell test pilot Bud Kelley.
	De Havilland H-1 Goblin test-flown in de Havilland Vampire, an example of coordinated design of aircraft and power plant by one firm.
Oct.	BMW-003A test-flown in Ju-88 flying test bed.
Nov.	Modified Meteor test-flown with two Metropolitan-Vickers F2's.
Dec.	NACA engine-research laboratory opened at Cleveland, immediately put to work on jet projects, including first full-scale test at altitude and speed conditions.

1944 *(early)*	Development of radically improved Jumo-004D and -004H and BMW-003D begins.
Jan.	I-40 turbojet test-run at General Electric (Lynn) factory, producing 3,600 lb thrust (shortly afterward, 3,750).
	Lockheed XP-80, powered by H-1 turbojet diverted by de Havilland from their second prototype of the D.H. 100 Vampire, test-flown. Milo Burcham at the controls; speed approached 500 mph, a figure exceeded shortly afterward.
	Germans start design of Jumo-012 and BMW-018 (-022 and -028 with propellers) units in the 6,000-lb thrust class.
	Westinghouse 19A makes first flight as booster unit on Goodyear FG-1 Corsair.
	Bristol Aeroplane Co. begins preliminary studies in gas turbine with heat exchanger, developing into the Theseus propeller-turbine.
Feb.	Rolls-Royce begins design of W2B41 Nene, with design thrust of 4,500 lb.
Mar.	Westinghouse 19B Yankee makes first test-run.
	Rolls-Royce Derwent I (B37) test-flown in Meteor III.
	Messerschmitt Me-262, powered by two Jumo-004B's, begins coming off assembly line. In limited combat action by late summer, mostly as bomber.
Apr.	General Electric axial-flow gas turbine TG-180 (J-35) test-run.
	First production model of Gloster F 9/40 Meteor, sent to USA in exchange for Bell P-59A, test-flown at Muroc Lake by Gloster test pilot John Grierson.
	British mission arrives at Muroc Lake, headed by H. Constant of the RAE and including Drs. Hooker and Griffith of Rolls-Royce and representatives from de Havilland and Power Jets.
May	Derwent modified with spur-reduction gear for propeller drive (later named Trent).
	Gloster Meteor, powered by two Rolls-Royce Wellands, goes into service with RAF fighter squadron (shooting down V-1 buzz bombs during summer).
June	Lockheed XP-80A (later named Shooting Star) test-flown at Muroc Lake, with Lockheed test pilot Tony Le Vier at controls.
1944 *July to Nov.*	Following experimental jet-bomber projects initiated: Douglas XB-43, North American XB-45, Consolidated Vultee XB-46, Boeing XB-47, Martin XB-48, Northrop XB-49.

Aug. Rolls-Royce Nene (B41) test-run.

Sept. Arado-234, powered by two BMW-003A8's, reaches altitude of 42,000 ft. Before end of 1944, in limited combat action, powered by Jumo-004's and BMW-003's.

Sept. Design of Derwent V, 85 per cent scaled-down version of the Nene, begun. Aim to provide a more powerful unit for the Meteor, in an attempt on the world's speed record. Thrust of 3,200 lb expected.

Oct. Bell XP-83, powered by two J-33 turbojets, test-flown at Muroc Lake, with Bell test pilot Bob Stanley at controls.

Allis-Chalmers receives contract to build Halford turbojets. (Ultimately 7 H-1B's were completed, one of which flew in the Curtiss XF15C as tail unit.)

Dec. He-162 Volksjaeger (designed in September as a high-priority emergency lightweight fighter with BMW-003A engine) test-flown.

Rolls-Royce Clyde propeller-turbine, with nine-stage axial compressor and low-pressure turbine, plus centrifugal compressor and high-pressure turbine, bench-tested. Designed for 3,000-shp, 600-lb exhaust jet thrust.

1945 *Jan.* McDonnell XFD-1 Phantom makes first test flights with two Westinghouse 19B's.

Production of General Electric I-40 switched to Allison to be designated "J-33-4-AL"; the TG-180 to Chevrolet, Tonawanda as "J-35."

First test-run of Metropolitan-Vickers F2/4, redesigned and improved version of F/2.

Feb. Westinghouse establishes aircraft gas-turbine division.

Pratt & Whitney given contract to build Westinghouse 19XB for the FD-1 and continue own developments in aircraft gas turbines.

Mar. Derwent V test-run, thrust of 3,000 lb.

Apr. Armstrong-Siddeley ASP (ASX geared for propeller drive) test-run, later called the Python.

July First test-run of Bristol Theseus gas turbine.

Sept. Lockheed P-80 flies in England with Rolls-Royce Nene as power plant, at speed of 580 mph.

Oct. Northrop XP-79, prone-pilot flying-wing experimental fighter, powered by Westinghouse 19B Yankee turbojet, and small rocket unit, test-flown at Muroc Lake, crashing during flight.

Nov. Meteor IV, christened "Britannia," flown by Group Captain Wilson and powered by two Derwent V's producing 3,500 lb static thrust,

breaks world's speed record, with three flights over closed course averaging 975 kph (606 mph).

July to Dec. Advanced experimental jet fighter and bomber projects initiated by AAF: McDonnell XP-85 with 24C instead of 19B unit, McDonnell XP-88, Northrop XP-89, Lockheed XP-90, Republic XP-91, and Consolidated XP-92; fast, medium-weight bombers (formerly A series), Martin XB-51, Boeing XB-52, Consolidated Vultee XB-53; also Curtiss XA-43 (since developed into the XP-87, with four 24C's).

Dec. De Havilland Vampire operates from aircraft carrier HMS *Ocean*, making first jet-propelled take-offs and landings on aircraft carrier.

1946

Jan. Consolidated Vultee twin-turbine experimental fighter XP-81, powered by GE turboprop TG-100 (T-31) and GE turbojet I-16 (J-31), test-flown at Muroc Lake.

Feb. Colonel William Councill flies P-80A nonstop across the country, Burbank to LaGuardia Field (2,470 miles), lowering record by more than one hour. Average ground speed, 584 mph. Time, 4 hr 13 min 26 sec.

Republic XP-84, experimental single-jet fighter powered by General Electric TG-180 (J-35) through-flow turbojet with axial compressor (4,000-lb thrust), test-flown at Muroc Lake at 590 mph.

May Douglas XB-43, AAF's first twin-jet bomber, adapted from Allison-powered pusher XB-42 Mixmaster, test-flown, powered by two TG-180 turbojets. Speed, over 500 mph.

July McDonnell FD-1 Phantom tested during maneuvers on flight deck of the battle carrier (CVB) USS *Franklin D. Roosevelt.*

Allison tests new model of J-33 turbojet.

Aug. Rolls-Royce Dart propeller-turbine, with two-stage centrifugal compressor and one-stage turbine, bench-tested. Designed for 1,000-shp, 350-lb exhaust jet thrust.

Sept. Group Captain Donaldson, flying the Gloster EE-549 Star Meteor, with Rolls-Royce Derwent-V turbojet souped up to produce 4,200 lb thrust at 15,200 rpm, achieves new world's speed record of 991 kph (616 mph) in an average of four runs at Rustington, near Tangmere airdrome.

Vickers Supermarine single-jet fighter, E10/44, powered by Rolls-Royce Nene I turbojet of 5,000 lb thrust, announced.

Oct. Chance Vought XFU6-1 Pirate, jet-powered successor to the Corsair, test-flown. Power plant is Westinghouse 24C turbojet.

Oct. North American single-jet experimental carrier fighter XFJ-1 (Navy version of AAF's XP-86), powered by General Electric TG-180, test-flown.

Republic XP-84 Thunderjet wins official American speed record of 611 mph at Muroc Lake.

Nov. First international jet-powered transport flight from London to Paris (Nov. 18) by the Nene-Lancastrian (two Nene I's outboard, two Merlins inboard). Return trip on Nov. 22 in 41 min broke record for Paris-London run.

Navy's all-turbine Ryan XF2R-1 (GE turboprop TG-100 in nose, GE turbojet I-16 in tail) test-flown at Muroc Lake.

Northrop-Hendy Turbodyne, development of which was begun in 1941, revealed at National Aircraft Show, Cleveland.

Russians fly turbojet fighter during an air-force exhibition. Craft may have contained German power plant captured during the final stages of World War II. (Later reported as 2 Jumo-004H units of 4,500-lb thrust.)

French-built Rateau A-65, 16-stage axial-flow unit, displayed at Paris air show.

Dec. Armstrong-Whitworth 52 experimental flying-wing aircraft powered by two Nene I's announced. Second prototype will have two Derwent V's buried in the wings.

A Nene I sent to U.S. for Taylor Turbine Corp. passed official A-N 150-hr type test at Naval Air Material Center, Philadelphia.

Menasco L-4000 turbojet, developed from Lockheed L-1000 reported ready for experimental bench-run.

AAF experimental jet bombers North American XB-45 and Consolidated Vultee XB-46, Martin XB-48, reported ready for flight tests early in 1947.

Navy's composite-powered Grumman XTB3F-1 torpedo bomber (2 Pratt & Whitney Double Wasp C engines and Westinghouse 24C turbojet) and Martin XP4M-1 patrol bomber (2 Pratt & Whitney Wasp Majors and General Electric I-40-4) test-flown.

Completion of transfer of TG-180 (J-35) production from Chevrolet and General Electric to Allison; development continues at GE.

Glossary of Technical Terms and Abbreviations

Aircraft engine—Conventional reciprocating-piston engine used in aircraft, radial or V-type, liquid, or air-cooled

Aircraft gas turbine—Gas turbine applied to aircraft propulsion, either to drive a propeller (turboprop) or by exhaust-jet thrust (turbojet)

Athodyd—A ramjet (name derived from AeroTHermO DYnamic Duct (*see* Ramjet)

Axial-flow compressor—A compressor that compresses air parallel to the axis of rotation of the rotor, which has several sets of blades, or "stages"

BHP—Brake horsepower

Centrifugal compressor—A compressor that discharges compressed air in a direction tangential to the rotating member of the impeller

Combustion chamber—A cylindrical device in which fuel is mixed and burned in a continuous flow of air

Combustion chamber, annular—Ring-shaped, single-cylinder type, as in Metro-Vickers F2, Westinghouse, and most of the German designs

Combustion chamber, multiple—Design featuring several combustion chambers in radial arrangement, as in the Whittle and GE axial types

Combustion chamber, reverse flow—Type in which the air enters and exhausts out the same end, as in the original Whittle engine and early Rolls-Royce and GE units

Combustion chamber, through-flow—Type in which fuel is injected at the compressor end and the compressed gases resulting from burning are passed directly to the turbine at the far ends of the combustion chambers, as developed by Halford (H-1), later R-R and GE types

Combustion cycle—Intake of air, compression, combustion, exhaust

Compressibility—Effects that occur when local velocities on propeller tips, parts of wings, etc., exceed the speed of sound, producing shock waves which result in a sharp increase in drag and other effects. Such effects may be encountered at a Mach number as low as 0.75 (570 mph at sea level, 495 mph at 35,000)

Compressor—A mechanical device for compressing air

Critical speed—The speed of an aircraft at which compressibility effects begin to be encountered, either in straight-powered flight or in a dive (shown by a red line on the air-speed indicator of military aircraft)

Duct—A tube through which a gas or fluid is conveyed

Engine—A mechanical device for converting physical energy, such as heat, into useful work

Exhaust collector—A conical transition section which conducts the exhaust gases from the turbine to the jet nozzle (the term is recommended instead of tail cone)

Gas turbine—A rotary engine turned by a current of gas

Heat exchanger—A device for the transfer of heat. In a gas turbine, hot gases from the exhaust are returned to the combustion-chamber area to increase the temperature of incoming compressed air

Impeller—A vane-carrying wheel that imparts energy to the air by its rotating action

Jet—A sudden rush of gas or fluid through a narrow opening or nozzle

Jet engine—A mechanical device used to create a sudden rush of gas or fluid through a nozzle

Jet nozzle—A tubular section or duct which connects on to the exhaust collector (the term is recommended instead of tail pipe)

Mach number—Named after the Australian scientist Ernst Mach (pronounced Mock), this term refers to the relationship of any speed to the speed of sound. Mach number 1.00 is equal to the speed of sound, or 760 mph at sea level (low-level Mach). At 35,000 ft and above, the speed of sound is 660 mph. This is also Mach number 1.00 (high-level Mach number). Mach-number variation with altitude is caused by change of temperature, not air density

Nozzle—A device used to convert fluid pressure into velocity

Propeller-turbine—Gas turbine for propeller drive (*see* Turboprop)

PSI—Pounds per square inch

Pulsejet (resojet)—Also known as "intermittent-duct engine" or "resonant jet engine" and consists of a simple duct or tube equipped with light, flap-type check valves, the successive explosions propelling the exhaust gases rearward and producing forward motion by reaction (as in the V-1 buzz bomb)

Ramjet—A suitably shaped duct equipped with fuel burners which gets its compression from forward motion or ram pressure, the heated gas being exhausted at a higher velocity than that at which it enters, producing a net reaction force

Rocket engine—Liquid-propellant type feeds a liquid fuel and liquid oxidizer by pumps into a combustion chamber; the two liquids react with or without ignition, continuing to burn as long as the supply lasts; no air is required. Dry type contains a self-combustible material, such as black powder

Rotor—A rotating wheel with axial-flow compressor blades

SHP—Shaft horsepower

SLST—Sea-level static thrust

Tail cone (not recommended)—*See* Exhaust collector

Tail pipe (not recommended)—*See* Exhaust collector, Jet nozzle

Thermal jet engine—A unit in which the propulsive gas is taken in from the atmosphere, heated by burning of a hydrocarbon, and exhausted at a higher velocity than that at which it entered

THP—Thrust horsepower, or shaft horsepower multiplied by the efficiency of the propeller, *e.g.*, 80 per cent at sea level and 400 mph. In the case of the propeller turbine, an addition must be made for the thrust of the jet

Thrust—Force or pressure directly exerted

Thrust/horsepower ratio—Formula for converting thrust into horsepower

$$\text{Hp} = \frac{\text{thrust (lb)} \times \text{air speed (fps)}}{550}$$

Example: 4,000 lb thrust equals 4,000 hp at 375 mph and 8,000 hp at 750 mph

Turbine blade or bucket—A part attached to the circumference of the turbine wheel and having a curved airfoil section, made of high-heat-resistant alloy

Turbine wheel—A rotating part of the turbine which converts the energy from the gases to useful work

Turbojet—Aircraft gas turbine for jet propulsion; a thermal-air-jet unit in which entering air is compressed by a rotary compressor, heated by the combustion of fuel at compressor pressure, released through a turbine that drives the compressor, and then ejected at high velocity through the rearward-directed exhaust nozzle

Turboprop (also propjet)—Aircraft gas turbine that drives the airscrew or propeller by means of reduction gear, with a portion of the heated compressed gases used for additional thrust through jet exhaust

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